Characterizing 25 years of change in the area, distribution, and carbon stock of Mediterranean pines in Central Spain

Running head: Mediterranean pine dynamics of Central Spain

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Abstract

Mediterranean pines are subject to continuous change under the influence of natural and human factors. Remotely sensed data provide a means to characterize these changes over large areas. In this study we used a time series of Landsat imagery to capture 25 years (1984-2009) of change in the pine dominated forests of the Central Range in Spain. Object-based image analysis methods were used to identify landscape-level changes in the area and distribution of forests. We also propose that absent disturbance, biomass accrual is occurring (or depletion in cases where removals are evident) and may be related to changes to the carbon stock; we describe the detected spectral changes in terms of biomass changes as the *carbon stocking process*. The primary inputs for the identification of changes in the area and distribution of pine stands were Landsat bands 3, 4 and 5 and the Tasseled Cap Angle (TCA)—a metric derived from the greenness and brightness components of the Tasseled Cap Transformation (TCT). In the identification of *carbon stocking processes* the derivative of the TCA, the Process Indicator (PI) was used to inform on the rate and directionality of the change present. Our results show that the total area of pine forest has increased by 40%, from 1211 to 1698 square kilometres during this period, with a variable rate of change. The distribution of pine dominated forest has changed as well: there is an area of 765 km^2 permanently covered with pines and 945 km^2 found to be temporarily occupied. Following the logic of the *carbon stocking processes* we propose, our findings show that at the end of the analysis period, 20% of the potential pine area is increasing its carbon stock and 40% of this area is experiencing a decrease.

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1. Introduction

Forests have been described as the most important land carbon sinks (Le Quéré *et al.* 2009) and therefore play a relevant role in the global carbon budget (Bravo *et al.* 2008). The global carbon balance is markedly altered by the extents of forests, as well as the biomass content per surface unit (Houghton 2005). The character of forests as a sink or source of carbon dioxide is determined by the ratio of respiration to net primary production (Law *et al*. 1999), and this relation is strongly influenced by the stand successional stage (Odum 1969) and health condition (Brown 2002). Net ecosystem carbon balances are complex and multifaceted, resulting in evaluation difficulties (Schulze *et al.* 2000). To reduce complexity, a simple rule for above-ground forest components is that mature stands are more stable stocks of carbon and growing stands are net sinks of carbon (Goetz *et al*. 2006), but the age at which a forest becomes a net carbon sink varies according to forest type, site productivity and other factors (Goward *et al*. 2008). However, while carbon capturing ability is difficult to determine, the stocking magnitude of a forest stand is undoubtedly proportional to the biomass it stores (Masera *et al*. 2003, Houghton 2007).

A map of the dynamics of distribution, biomass content and succession stages of forests through time is an invaluable tool for spatially explicit assessment of forest carbon stocks, sinks and sources (Powell *et al*. 2010). Together with a timeline of change events, the effectiveness of management approaches can be evaluated (Hayes and Cohen 2007, Huang *et al.* 2009). Medium spatial resolution remotely sensed data (i.e. 10-100 m pixel) is well suited for characterizing forest change (Wulder *et al.* 2008a) and is the only feasible, cost-effective option for extensive areas (Lunetta *et al.* 2004). Since 1972 the United States Geological Survey (USGS) has been archiving Landsat imagery. In 2008 the USGS opened the archive to unfettered public access to analysis ready imagery (Woodcock *et al*. 2008), removing access and cost limitations and creating myriad opportunities for characterizing both spatial and temporal landscape processes (Goodwin *et al*. 2008, Olsson 2009, Verbesselt *et al*. 2010, Potapov *et al*. 2011).

In this work we aim to characterize the changes in area, distribution, and carbon stocking processes of pines in the Central Range of Spain during a period of twenty-five years (1984-2009) with a medium spatial resolution time series of images from the Landsat program. We apply a *multilevel object oriented* methodology for identification and classification of pine dominated areas, and analyse trends in carbon stocking processes at the stand level with an index derived from the Tasseled Cap Transformation. The specific objectives of the study are:

1. To assess changes in extent of a Mediterranean forest, where natural change is relatively slow and human induced change has historically been controlled, with a multilevel object oriented methodology.
2. To identify with spatial precision the distribution of pines in the Central Range of Spain and variations occurring in three sub-periods during the last twenty-five years (1984-2009).
3. To characterize carbon stocking areas with an index derived from the Tasseled Cap Transformation (TCT), assessing trends of change over a twenty-five year period (1984-2009).

2. Background

2.1 *Mediterranean pine forests*

Mediterranean forests and woodlands cover 73 million hectares, approximately 8.5% of the Mediterranean basin region (EFI 2009) and are of notable richness in species diversity (Myers *et al*. 2000). In Mediterranean ecosystems, pine forests generate non-wood products (Calama and Montero 2007) and serve important ecological functions including water regulation, erosion control, and provision of recreational opportunities and wildlife habitat (Merlo and Croitoru 2005). Pine forests have a significant carbon sink capacity that could help signatory countries of the Kyoto protocol achieve their targets for reduction of greenhouse gas emissions (Myneni *et al.* 2001).

2.2 *Monitoring change in Mediterranean forests*

In Spain, similar to other Mediterranean countries, a National Forest Inventory (NFI) provides periodical detailed data for assessment of biomass and carbon pools through sampling and reporting supported by statistics (MMA 2008). The NFI's ten-year re-measurement cycle enables comparison of data over time, but similar to other sample-based NFIs has some known limitations, including the discrete character of the sampling, which obliges extrapolation of data (Salvador and Pons, 1998), and the use of different basic cartography in subsequent updates of the NFI database (Villaescusa *et al*. 2001). Also, a decade can be too long an interval in areas undergoing rapid change that need up-to-date information and more frequent reporting on change events (FAO 2010). A few works have explored the potential of remotely sensed data in quantifying change in Mediterranean environments (table 1) especially integrating both forest disturbance and recovery; to the best of our knowledge no one has developed a methodology for characterization of carbon stock change focused upon this unique ecosystem.

Table 1. Studies of change in Mediterranean forests with remote sensing technology.

Study	**Environment (Country)**	**Satellite - Sensor (period)**	**Spectral variable**	**Parameter estimated**
Maselli *et al*. (1998)	Coniferous & Broadleaved (Italy)	Landsat - TM NOAA - AVHRR (1990)	Spectral Mixture Analysis NDVI	Vegetation cover
Maselli (2004)	Coniferous & Broadleaved (Italy)	NOAA - AVHRR Landsat - TM, ETM+ (1986-2000)	NDVI	Forest condition
Filella *et al*. (2004)	Shrubland (Spain)	Field spectroradiometer (1999-2002)	NDVI, PRI	Biomass
Vicente Serrano *et al.* (2008)	Coniferous (Spain)	Landsat - TM, ETM+ (1984-2007)	NBR NDVI	Vegetation recovery after fire
Roder *et al*. (2008)	Shrubs & pines (Spain)	Landsat - MSS, TM, ETM+ (1975-2000)	Spectral Mixture Analysis Reflective bands	Post fire succession
Minchella *et al*. (2009)	Pinewood (Italy)	ERS - SAR (1999-2003)	Backscattering amplitudes	Vegetation recovery after fire

Note: TM, Thematic Mapper; ETM+, Enhanced Thematic Mapper Plus; MSS, Multi Spectral Scanner; NOAA-AVHRR, National Oceanic and Atmospheric Administration- Advanced Very High Resolution Radiometer; NDVI, Normalized Difference Vegetation Index; PRI, Photochemical Reflectance Index; ERS-SAR, European Remote-Sensing Satellite Synthetic Aperture Radar.

2.3 *Retrospective analysis of change*

Monitoring change over large areas, and particularly historical change, is only feasible with satellite data (Nielsen *et al.* 1998, Townsend *et al.* 2009). Satellite imagery provides consistent and repeatable measurements at an appropriate spatial scale (Kennedy *et al.* 2007) for regional land cover assessment. The repetitive data acquisition, synoptic view and digital format suitable for computer processing have made remotely sensed imagery the major data source for change detection during the past decades (Wulder *et al.* 2008a). Medium spatial resolution satellite sensors such as those of the Landsat series (Multi Spectral Scanner (MSS), Thematic Mapper (TM), and Enhanced Thematic Mapper Plus (ETM+)) are well suited to capture forest cover and change at the stand level in support of research and reporting, relating both natural and anthropogenic drivers of change (Achard *et al*. 2007, Olander *et al.* 2008; White et al. 2011).

Now that almost four decades of Landsat imagery have been made freely available to the public (Woodcock *et al.* 2008), an unprecedented opportunity for change research has emerged. The study of a time series of images (i.e. > 2) has two main advantages over the use of traditional two-date change detection approaches: the first is the ability to study long-term trends in spectral response (Vogelmann *et al.* 2009) while controlling for the variability associated with solar angle, atmospheric effects (Wulder *et al.* 2008b) and phenology (Sonnenschein *et al*. 2011). The second advantage is the opportunity to determine rates of change (Gillanders *et al.* 2008a).

Extensive research is currently directed at assessing historical change in boreal and temperate forests with increasingly sophisticated image processing algorithms (e.g. Olsson 2009, Huang *et al*. 2009, Powell *et al*. 2010, Kennedy *et al*. 2010) that take advantage of the temporal information leveraged by a dense series of calibrated images. Long-term change in Mediterranean forests with an image trajectory approach remains to be further explored.

3. Methods

3.1 *Study area*

The area of interest covers approximately one million hectares in the Central Range of Spain, occupying part of the Ávila, Segovia, Madrid, Guadalajara and Toledo provinces. It is centred at latitude 40º 37’ 56’’ N and longitude –4º 6’ 47’’ E. Pines (*P.sylvestris* L., *P. pinaster* Ait., *P. nigra* Arn.) are the dominant tree species, except in the most western area where broadleaf species (*Quercus pyrenaica* Willd.) dominate. Forests extend to elevations of 2000 m, beyond which, shrubs (*Cytisus sp.*, *Genista sp.*, *Erica sp.*, *Echinospartum sp.*) are the prevalent vegetation (Rivas-Martínez 1963).

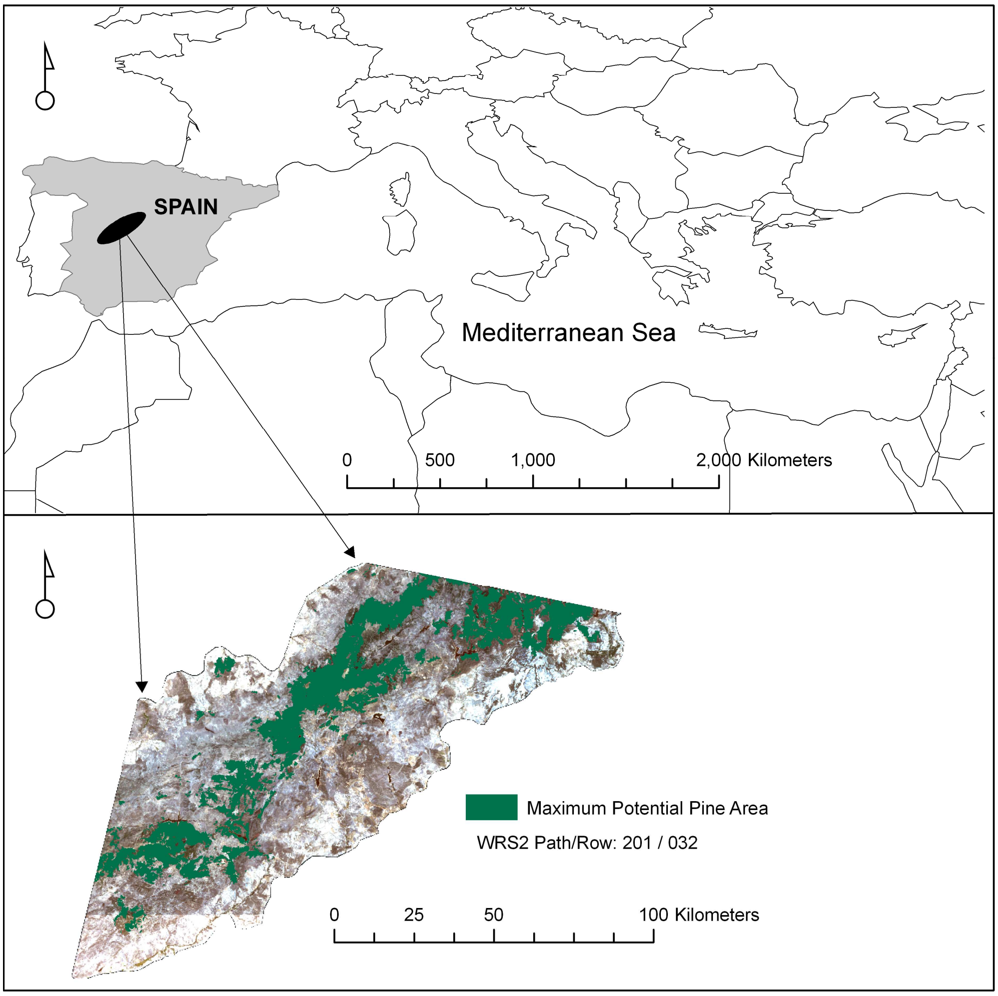

Figure 1. Location of the study area.

3.2 ***Satellite images***

With the recent public access to the Landsat archive (Woodcock *et al.* 2008) it is now possible to freely download over the Internet (glovis.usgs.gov) a time series of imagery for almost any area of the Earth (Wulder *et al*. 2011). As an additional source of data, the Spanish Instituto Geográfico Nacional (IGN) is compiling and pre-processing abundant Landsat imagery since 2008 as part of the Plan Nacional de Teledetección (PNT) and making it available for research (Villa *et al*. 2009).

Still, the acquisition of a historical time series of multiple adjacent Landsat images (relatively cloud-free) is a complicated task (Homer *et al.* 2004). We focused our research on a single Landsat scene (WRS-2 Path 201, Row 032) (figure 1) as it encompasses the most extensive continuous pine stands of the Central Range. Anniversary images were selected when possible (table 2), as recommended for monitoring studies (Wulder and Franklin 2002). In order to capture stable phenological conditions and to avoid the presence of snow in high altitudes, summer images were selected. The spectral suitability of early summer images (years 2000, 2001, and 2005) was thoroughly checked through the processing stages to detect and avoid possible phenology artefacts.

Table 2. List of Landsat images used in the study. Reference image for radiometric normalization (22/08/2000) is highlighted.

Landsat / Sensor	Source	dd/mm/yyyy	Sun elev.
5 / TM	EarthExplorer	18/08/1984	52.89
5 / TM	EarthExplorer	11/08/1987	54.11
4 / TM	EarthExplorer	11/08/1990	54.38
4 / TM	EarthExplorer	14/08/1991	51.68
7 / ETM+	EarthExplorer	22/08/2000	54.87
7 / ETM+	EarthExplorer	06/06/2001	64.24
5 / TM	EarthExplorer	17/06/2002	62.20
5 / TM	EarthExplorer	07/08/2003	56.50
5 / TM	Aurensis	25/08/2004	53.15
5 / TM	Junta de Castilla y León	24/05/2005	62.80
5 / TM	EarthExplorer	23/08/2009	54.48

Our time series consisted of nine Landsat TM and two ETM+ (Scan Line Corrector (SLC) on) images. To ensure a more complete time series, we increased our tolerance for a small amount of cloud cover in the images, but still, a yearly time series of images was not possible to obtain and the time step is not constant; there is a gap in images in the 1990s corresponding to the private sector distribution era (Tolomeo *et al*. 2009). Longer intervals between images may reduce detection accuracy for subtle changes (Wilson and Sader 2002, Jin and Sader 2005).

3.3 *Auxiliary data*

The *Mapa Forestal Español* (MFE50) is the digital version of Ruiz de la Torre forest map of Spain for the year 2000. In the construction of this map the source of data consisted of aerial photography and field notes. Polygons interpreted on photography were transferred to the 1:50 000 National Topographic Map (MTN) and the paper map version was later digitized. This GIS database encompasses 68 attributes to characterize vegetation units. Some relevant attributes for identification of pine forest areas are *dominant species* and *crown cover* (that is, the proportion of area covered by the horizontal projection of the canopy (in percentage).

Field data from plot-based inventories such as the NFI and other local management plans were used at various stages of the research, being of particular value in the accuracy assessment during the confidence building stages. Standard forest variables such as species, number of trees per plot and diameter at breast height are measured and updated on a decadal basis.

3.4 *Pre-processing*

All images were orthocorrected with a 30 m Digital Elevation Model (DEM) derived from 1:10 000 digital cartography (sitcyl.org) and co-registered to the UTM 30N (datum WGS84) coordinate system with root mean square errors (RMSE) of less than half a pixel. Twenty-five ground control points were manually identified in the images and used for adjustment.

A robust radiometric correction is essential in change detection applications (Lu *et al.* 2004, Coppin *et al.* 2004) and when image values are related with biophysical phenomena (Gong and Xu 2003). It is particularly challenging if images from various sensors are included in the analysis (Roder *et al*. 2005). We applied a relative radiometric normalization to the sequence of images; the reference image was selected in the middle of the time series for its good quality and absence of haze (table 1).

Digital Numbers (DNs) were converted to Top of Atmosphere (TOA) reflectance following instructions and recommended coefficients from Chander et al. (2009), which give the recommended calibration for each Landsat sensor (including changes occurring over the lifetime of a given sensor). Atmospheric effects on the reference image were corrected with the cosine-Theta (COST) model (Chávez 1988). All other images were normalized to the reference image with the Iterative Reweighted Multivariate Alteration Detection (IR-MAD) process (Canty et al. 2004)—an automatic ordination algorithm recommended for spectral trajectory analysis (Schroeder et al. 2006). Image normalization transforms images to a common radiometric scale, minimizing sun, sensor and view angles, as well as atmospheric differences among images. The process of normalization reduces the amount of artefacts due to illumination or atmospheric variations, enabling more reliable detection of true change (Song *et al*. 2001).

3.5 *Tasseled Cap Transformation (TCT) and Tasseled Cap Angle (TCA)*

The Tasseled Cap Transformation (TCT) (Kauth and Thomas 1976, Crist and Cicone 1984, Crist 1985, Huang *et al.* 2002) has been broadly employed in forestry studies of structure (Hansen *et al*. 2001, Cohen *et al*. 2001), condition (Wulder *et al.* 2006, Healey *et al.* 2006), successional state (Peterson and Nilson 1993, Helmer *et al.* 2000) and change detection (Lea *et al*. 2004, Jin and Sader 2005) in various forest environments.

The TM brightness (B) component is by definition (Crist and Cicone 1984) a positive value, whereas the greenness (G) component depends on the contrast between visible and near-infrared bands (table 3), with exposed soil having negative values (Gillanders *et al.* 2008b, Price and Jakubauskas 1998) and vegetated areas positive values. G and B components define the so called by Crist and Cicone (1984) *vegetation plane* (figure 2). Studying the spectral behaviour of forest stands in the *vegetation plane* provides insights into forest cover densities and forest development stages (table 4).

Table 3. Coefficients used for calculation of Thematic Mapper TCT indices.

Sensor	Component	Red	Green	Blue	NIR	SWIR1	SWIR2
TM	Brightness	0.3037	0.2793	0.4343	0.5585	0.5082	0.1863
	Greenness	-0.2848	-0.2435	-0.5436	0.7243	0.0840	-0.1800
ETM+	Brightness	0.3561	0.3972	0.3904	0.6966	0.2286	0.1596
	Greenness	-0.3344	-0.3544	-0.4556	0.6966	-0.0242	-0.2630

Table 4. Literature with results based on the spectral performance of forests in the vegetation plane.

Study	**Environment (Country)**	**Research goal**	**Findings**
Peterson and Nilson (1993)	Mono-specific pine and birch (Estonia)	Development stages	Asymptotic tendency towards G saturation of secondary succession trajectories
Cohen *et al*. (1995)	Coniferous (Oregon, USA)	Cover densities & Development stages	Different cover classes occupy a different position in the vegetation plane; trajectories of development stages were hypothesized
Price and Jakubauskas (1998)	Coniferous (Wyoming, USA)	Development stages	Changes in spectral reflectance associated with succession in coniferous forests follow a defined path or vector in spectral in spectral brightness greenness space
Cohen *et al*. (1998)	Coniferous (Oregon, USA)	Cover densities	Mapping clearcuts benefiting form the high G and low B that dense forests have relative to clearcuts
Steininger (1996)	Tropical forest Amazonas (Brazil)	Development stages	Greenness is sensitive to regrowth canopy changes of young stands, while brightness is most sensitive in later years
Powell *et al*. (2010)	Mesic to xeric coniferous (Arizona, USA) Mixed deciduous and coniferous Minnesota (USA)	Biomass	Modelling biomass with TCT derived indices, including the TCA and $distance_{bg}$
Duane *et al*. (2010)	Coniferous (Oregon, USA)	Mapping stand age and carbon stock	The TCT derived index $distance_{bg}$ is strongly correlated with stand age
Gómez *et al*. 2011	Coniferous (Alberta, Canada)	Forest dynamics	Characterization of the states (patterns) and processes of change in a dynamic forest

Note: $distance_{gb} = SQRT(TCB^2 + TCG^2)$ where TCB is Tasseled Cap Brightness and TCG is Tasseled Cap Greenness.

A range of studies in coniferous forests have confirmed higher values of G and lower values of B in dense forest cover classes when compared to open stands or clearcuts (Cohen *et al*. 1995, Healey *et al.* 2005). The Tasseled Cap Angle (TCA) index, defined as the angle formed by G and B in the vegetation plane (equation 1) and first used by Powell et al. (2010) for modelling biomass in coniferous and mixed forests of Arizona and Minnesota (USA), condenses the G/B information to a single value (Gómez *et al*. 2011): dense forest stands exhibit higher values of TCA than open stands or bare soil (figure 2).

$$TCA = \arctan (G/B) \quad (1)$$

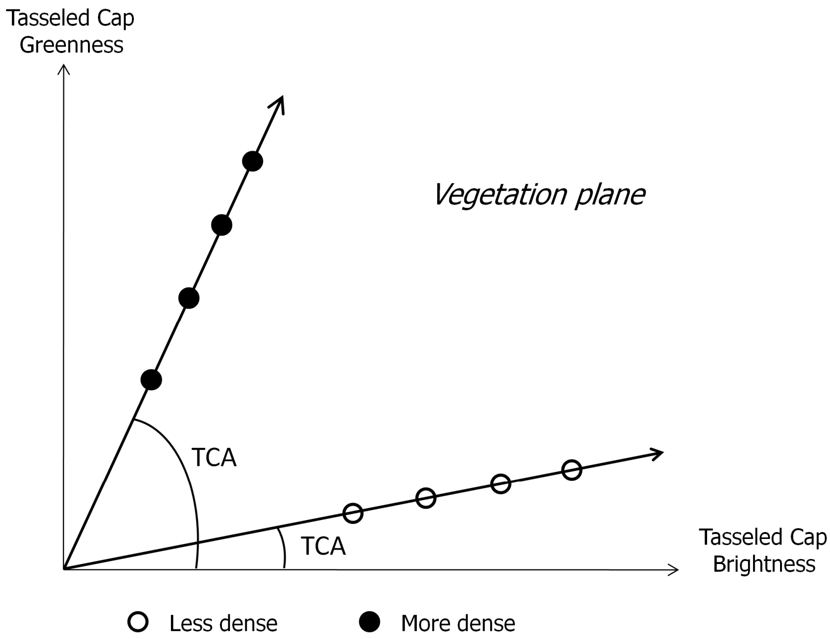

Figure 2. Vegetation plane formed by the Tasseled Cap Transformation Greenness and Brightness Components. The TCA is the angle formed by these components: TCA = arctan(G/B).

Considering these notions, we explored the relationship of the TCA to forest density variables at the stand level in the Mediterranean pines of the study area. Data from plot-based field inventories were krigged to 30 m spatial resolution and regressed with values of the TCA at the stand level. The entire range of BA representative of the study area was included in the correlation analysis. To support later analyses, we find that, as expected, the TCA and BA are linearly related, with a high and positive value of correlation (coefficient of determination $R^2 = 0.80$).

We calculated the angle between normalized G and B components (equation 1) for our time series of images. As derived from the TCT, the TCA range of values is scene dependent (Crist and Cicone 1984). Based on the strong relation between TCA and density variables in the study area we posit that analysing the TCA values over a time series of images provides information on relative changes in the density of forest stands: the TCA is stable if there is no change in density (constant BA); an increment in BA (e.g. natural regeneration or plantation, stand maturity or increase of crown closure) results in a concomitant increase in the TCA and conversely, when the BA diminishes (e.g. after a partial harvest or thinning operation, or after a disturbance such as a fire), the TCA value decreases (figure 3). The eleven TCA layers were combined in a single image, noted hereafter as the TCA image.

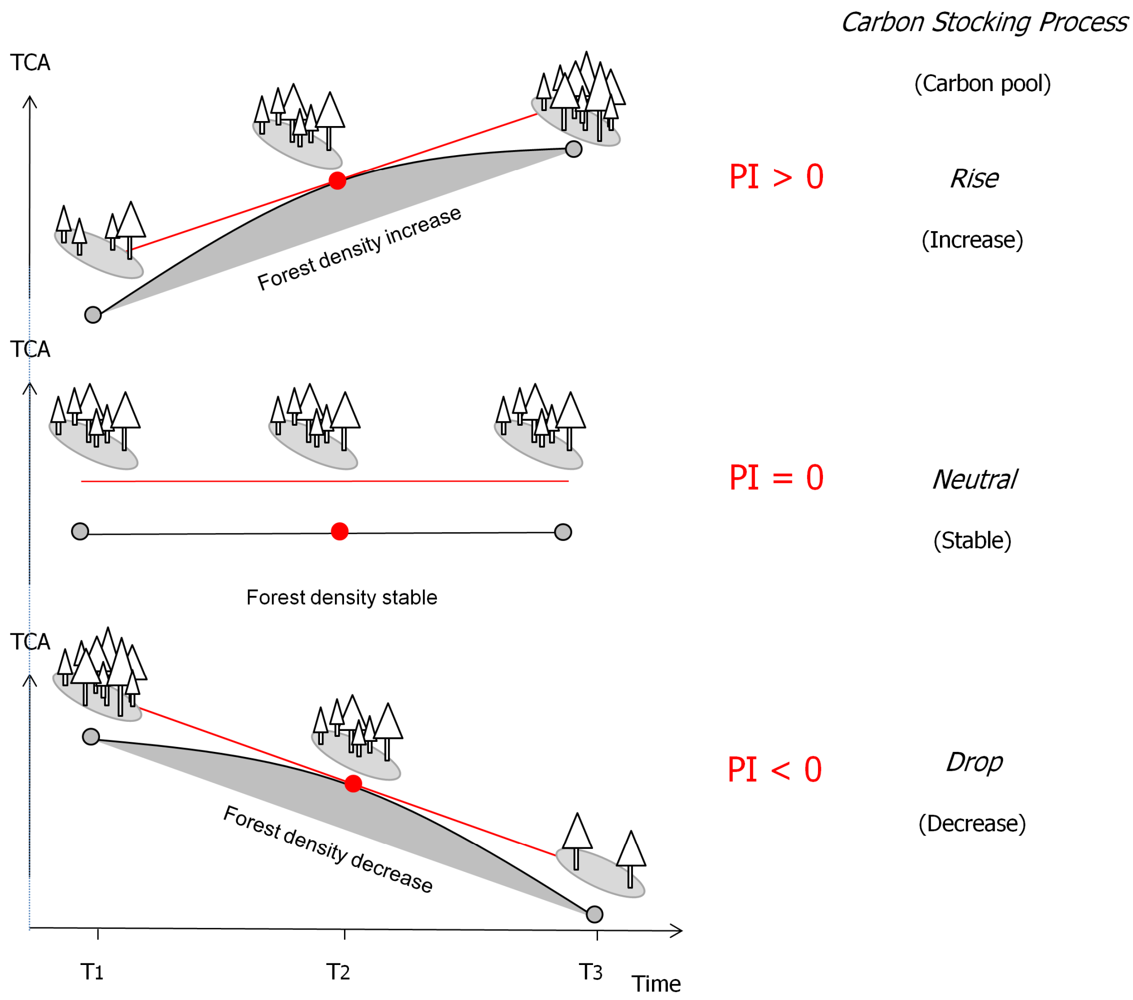

Figure 3. Process Indicator (PI) and carbon stocking processes.

3.6 *The Process Indicator (PI)*

Each pixel TCA profile was approximated with a Lagrange second order polynomial (which enables interpolation with uneven intervals among occurrences), and its derivative with respect to time (years) was calculated. The result is a multiband spectral image with the same number of bands as the original TCA image, which we define as the Process Indicator (PI) image (Gómez *et al*. 2011). The PI image illustrates at each pixel the rate of TCA change over time. As the TCA provides information about the relative forest density at each date, the PI similarly gives information on the rate of change in forest density at each time. For example, a high positive value of PI indicates a relatively fast rise of TCA, (e.g. a stand rapidly augments density by rapid growth or quickly develops towards crown closure); a high negative value of PI indicates a relatively fast drop of TCA value (and stand density) (e.g. after a stand replacing disturbance or a strong thinning). Moderate values of PI refer to slow and slight changes in TCA value, such as a lowered density after a partial harvest (negative PI) or increasing density with slow natural growth or development (positive PI). Relative changes in carbon pools associated with changes in forest density can be similarly assessed (figure 3). PI values are direct indicators of processes of change and constitute a practical tool to monitor temporal relative changes; for an estimation of absolute values of change, a thorough calibration of the index would be required.

3.7 *Classification of pine dominated areas and change over time*

To identify pine dominated areas and assess changes in extent and distribution over the period 1984-2009, we implemented a methodology supported by a supervised classification based on objects. Four images that divide the period into three epochs of approximately similar duration (i.e. 1984-1990, 1990-2000 and 2000-2009) were independently classified. Input data for classification were normalized bands 3, 4 and 5 of the Landsat image, and the TCA layer, which incorporates information on vegetation density. Each of the four images was individually segmented into three hierarchical levels (scale parameter 1, 2 and 5; colour-shape 0.9-0.1; smoothness 0.5) with Definiens Cognition Network Technology® (Baatz and Schäpe, 2000; Definiens, 2005). Only one class (*pine*) was to be retained but we considered a seven class scheme to reduce the error in change detection (Fuller *et al.* 2003). The image dated 2000 was classified first and its accuracy assessed with reference data from the MFE (Mapa Forestal Español) and NFI. The nearest neighbour classification algorithm used in classifying the other three images was trained with the spectral signatures of samples acquired for the reference classification (i.e. year 2000 image); in so doing the robustness of the radiometric normalization assured comparable results. Objects classified as *pine* in any of the three hierarchical levels (scale 1, 2 and 5) were merged and the resulting areas at each date (i.e. 1984, 1990, 2000 and 2009) were compared in a GIS for an assessment of change.

3.8 *Assessment of carbon stocks*

We defined the *Maximum Potential Pine Area* (MPPA) for the period 1984-2009 as the overall union of *pine* areas at any of the four dates considered. The MPPA represents the maximum extent occupied by pines at any time during this period, and it encompasses a region persistently occupied by pines (*Permanent*) and other areas that have only been intermittently covered with pines during the last 25 years (*Intermittent*) (figure 4).

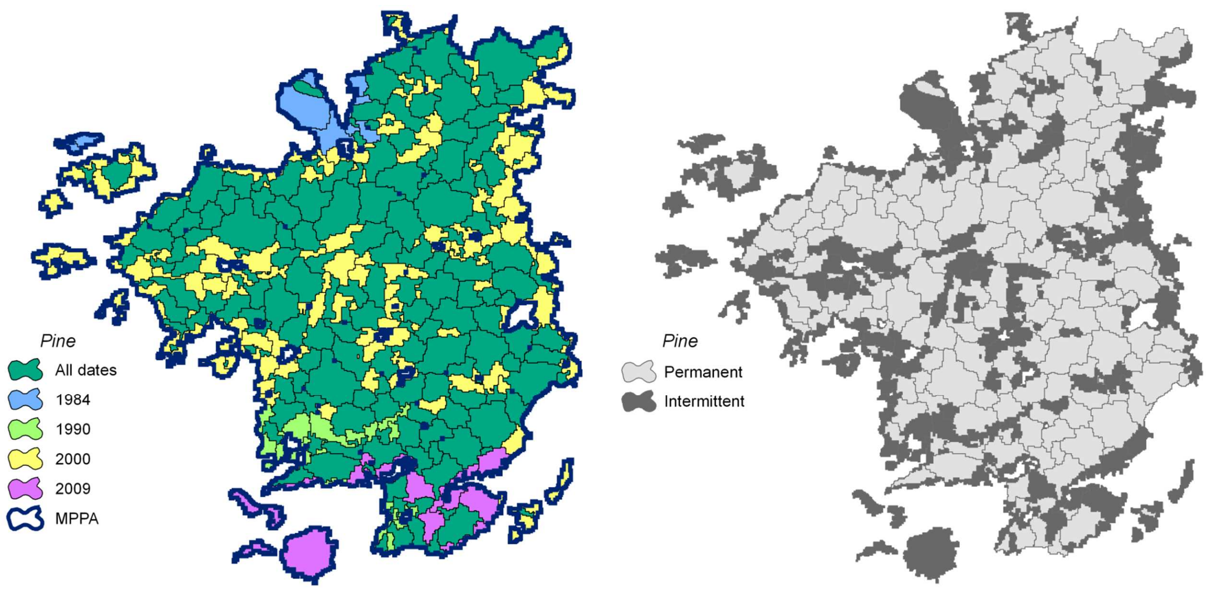

Figure 4. Schematic definition of the MPPA, Permanent and Intermittent areas.

Segmenting the landscape into homogeneous spatial units facilitates visualization and analysis of its properties. There is no unique way of partitioning the landscape for ecological analysis (Burnett and Blaschke 2003) and no single spatial scale is optimal for characterizing the multiple options into which it can be divided (Hay *et al.* 2005). We chose the TCA 2000 image, completely free of clouds, for delineation of reference units for analysis (also in keeping with the classification reference image used). The parameters applied for definition of spatial units with homogeneous forest density at this date (year 2000) were scale 10, colour 0.9, and smoothness 0.5. Internal variation of the TCA (and forest density) in these segments is lower than the difference with their neighbours (Definiens 2005). Objects affected by small cloudy patches or cloud shadows in any of the images were excluded from analysis.

Relative rates of change of the TCA (surrogate of forest stand density) and concomitant relative rates of change of carbon stock associated with each segment were examined with its *Process Indicator* value at each date. Trends and rates of change of carbon stocks were analysed and statistically assessed.

4. Results

4.1 *Change in area and distribution*

The applied method enabled the assessment of the area and distribution of pines in the Central Range and also the description of changes that occurred over the 25 year period from 1984 to 2009 with spatially explicit detail. For an exhaustive account of changes in the area occupied by pines in each sub-period (i.e. 1984-1990, 1990-2000 and 2000-2009), the following concepts are used:

- *Stable: area classified as pine on the initial and final date of the analysis period.*
- *Increment: area classified as pine on the final date but was a different land cover class on the initial date of the analysis period.*
- *Reduction: area classified as pine on the initial date and not on the final date of the analysis period.*
- *Net change: Increment - Reduction (>0 or <0).*
- *Changed: Increment + Reduction. Area subject to change.*
- *Potential area: Stable + Changed. Area occupied by pine on initial and/or final date of the analysis period.*

From the initial date (1984) to the final date (2009) there has been a 40% increment in the area dominated by pine species, a result confirmed by the NFI updates (NFI2 and NFI3) (González-Alonso 2006) and mainly attributed to agricultural land abandonment. During the first sub-period (1984-1990) there was abundant transformation: an extent equivalent to 57% of the original pine area changed, producing a net increment similar to 36% of the original extent. In the second sub-period (1990-2000) the amount of area changed was less notable, equivalent to 33% of the extent of pine on the initial date (1990) and with a net loss of 17% of the pine dominated area. This decade maintained the most extensive stable area of the three sub-periods. In the course of the last sub-period (2000-2009) the *Increment* was 3.6 times the *Reduction* of the pine area, resulting a *Net change* equivalent to 25% of the area occupied by pines in 2000. All results are summarized in table 5 and mapped in figure 5.

Table 5. Pine area and changes during three sub-periods.

Year	Pine area (ha)	Period	Increment *(% of initial)	Reduction *(% of initial)	Net change *(% of initial)	Changed *(% of initial)	Potential *(% of initial)	Stable *(% of initial)
1984	121144							
		1984-1990	56496 *(46.6)*	12858 *(10.6)*	43638 *(36.0)*	69354 *(57.2)*	177365 *(146.4)*	108011 *(89.2)*
1990	164622							
		1990-2000	12502 *(7.6)*	41306 *(25.1)*	-28804 *(-17.5)*	53808 *(32.7)*	177023 *(107.5)*	123215 *(74.8)*
2000	135980							
		2000-2009	47149 *(34.7)*	13001 *(9.6)*	34148 *(25.1)*	60150 *(44.2)*	182757 *(134.4)*	122607 *(90.2)*
2009	169825							
Overall Total stable								91349
Overall Total potential								197144

** Equivalent to the area at initial date of the sub-period*

Pines cover a discontinuous area in the Central Range, frequently broken up by topographic features and human activities such as agriculture or urban development. Three regions or units can be distinguished in the study area: a central region of almost continuous and permanent pine coverage (B figure 5); a southern relatively large region with discontinuous spatial and temporal pine coverage (A figure 5); and a smaller region (C figure 5) with a high proportion of permanent pine coverage. As a general rule, changes in the distribution of pines have occurred at the boundaries of permanently covered areas in all three regions (figure 5). Increments in the pine area, probably motivated by natural colonization or by plantation of agriculture abandoned lands were common in the three regions during the period 1984-1990, mostly located in region C during the intermediate period (1990-2000) and particularly frequent in region A during period 2000-2009. On the other side, reductions of the pine area were more frequent in region C during the initial period, distributed across regions A and B during the intermediate stage and similarly distributed across regions A and C in the last period (2000-2009). Clear cutting is a forestry technique in disuse in the Central Range and all wood extractions are now of low intensity; however, a few stand replacing disturbances due to fire have been identified.

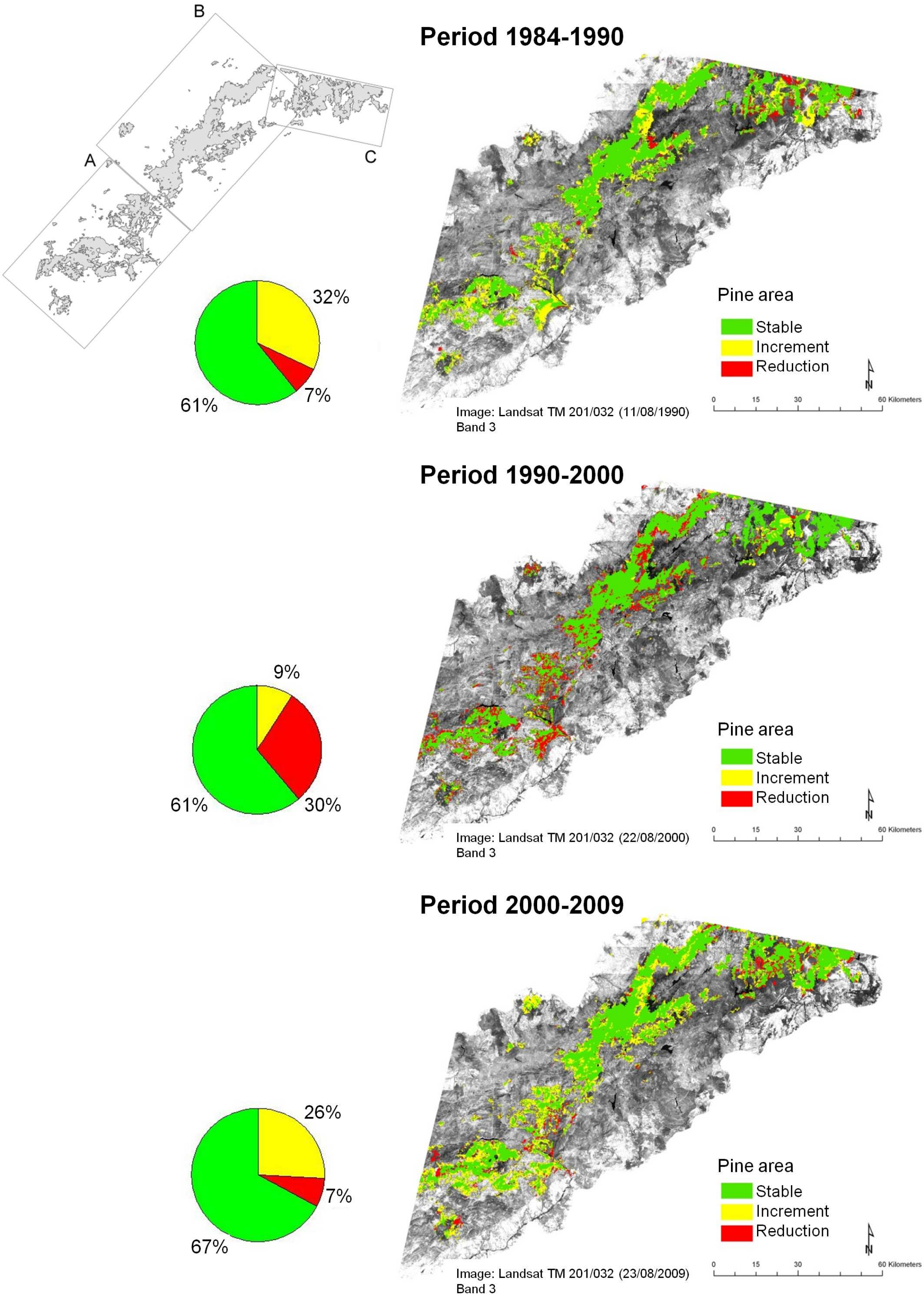

Figure 5. Maps of stable and changed area in three periods (1984-1990, 1990-2000 and 2000-2009). Green is the area that remains as pine during the period, red shows the reduced pine area and yellow shows the increased pine area. The study area (top left inset) is divided in three sections (A, B, and C) to facilitate the description of change over the three periods of interest.

4.2 *Classification accuracy assessment*

A thematic accuracy assessment aims to provide information on the validity of the results and it can only be as good as the reference data used (Foody 2009). We assessed the accuracy of the *pine* class in the year 2000, for which field data were available. Our confidence that other classifications have similar validity is based on the robustness of the radiometric calibration and normalization applied and the transference of spectral signatures. The process of accuracy assessment was specifically designed for this application; it includes the steps described by Congalton and Plourde (2001) and provides information of the classification reliability.

After visual inspection and approval of the map, field plot data of the NFI3 (dated 2000) were referenced for specific analysis of the *omission error* incurred, i.e. pine areas on the ground that our image classification did not capture. Ninety-two percent of the pine dominated NFI3 plots (730 plots) fell inside *pine* classified segments; some of the remaining NFI3 pine dominated plots had very low coverage fraction (below 20%), a criterion for exclusion from our *pine* class. Consequently, seventeen plots (2% in number) were in error by omission. To assess the magnitude of the *commission error* (i.e. areas classified as *pine* that were not considered as such by the reference data) a surface approach was implemented. Because assessing the accuracy of objects with punctual field measures is especially difficult in a non-homogeneous landscape, we used the MFE for assessment of the *commission error*. When a level 5 *pine* segment was outside an MFE pine polygon, it was deemed erroneous: this occurred in 181 cases (an area representing 1.8% of the total classified pine area). The MFE had been derived using generalization criteria that make it not adequate enough for assessment of our lower levels of segmentation and classification.

4.3 *Trends in landscape carbon stocking*

After segmenting the MPPA and vetting cloud and cloud shade affected segments, 5042 objects remained for analysis, representing the extent and percentages shown in table 6.

Table 6. Characteristics of the Maximum Potential Pine Area (MPPA) segments after vetting and removing cloud affected objects.

	N objects	Area (ha)	Average size (ha)	Area percentage
Permanent	1981	76545	38.6	44.7
Intermittent	3061	94570	30.9	55.3
Potential	5042	171116	33.9	100.0

Change in carbon stock was evaluated over the MPPA. The global average PI indicates the average performance of these forests as carbon pools; studying how the average PI changes over time permits inference of carbon stock trends. A low average of PI during the 25 year period, in the range -15 to 15, reveals the overall carbon neutral quality of these pine forests: on average the rate of change of carbon stocks is slow. The highest PI average occurred in 2000 (average PI 12.91) and the lowest PI average in 2002 (average PI -11.91, figure 6(*a*)). Prior to 1990 the mean PI is relatively low and remains steady; from 1991 to 2000 the PI tended to increase, but our scarcity of data during this time period precludes detailed description. In the last decade there is a tendency towards lower PI averages, with transitional fluctuations (figure 6(*a*)); in this time period higher values of the PI standard deviation denote the increasing complexity of landscape carbon pools.

It is worth emphasizing that the PI is an indicator of processes and not of states; it does not enable estimation of absolute carbon stocks, but indicates relative rates of change in carbon stocks: a positive PI value indicates the forest is in a process of augmenting its carbon storage (e.g. density increment by natural growth); a negative PI value indicates the forest is in a process of reducing its carbon storage (e.g. diminution of density in a thinning operation).

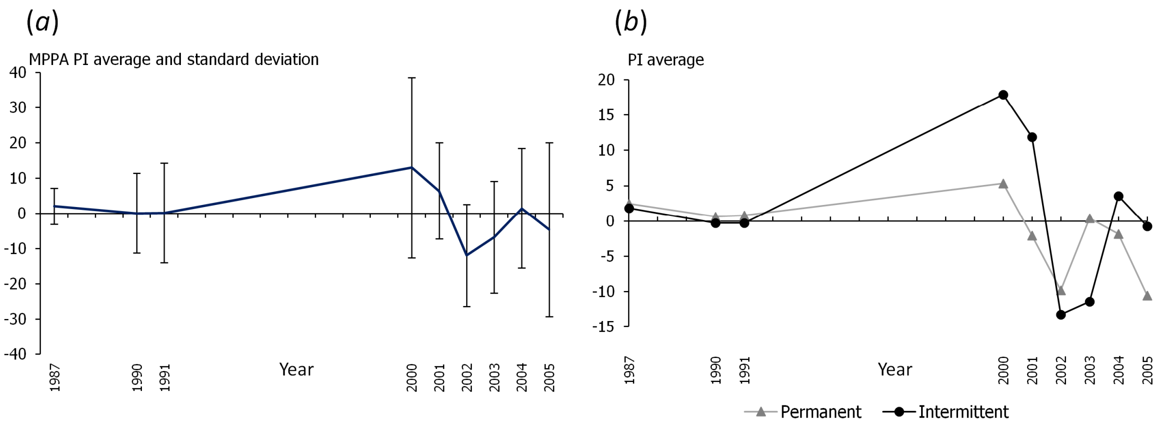

Figure 6. Average PI values during period 1984-2009. (a): average and standard deviation in the area; (b): average values for the permanent and intermittent areas.

Changes over time of the PI average follow a similar trend in areas of *permanent* and *intermittent* pine coverage (figure 6(*b*)). Maximum and minimum PI values are coincident in time: year 2000 is the maximum PI—i.e. the maximum average rate of positive change (fast rise of carbon stocks); year 2002 is the minimum PI—i.e. the minimum average rate of negative change (fast drop of carbon stocks). However, fluctuations of the PI average are notably more accentuated in the *intermittent* area. The PI standard deviations and range of values are lower in *permanent* than in *intermittent* areas (table 7), corroborating the more stable character of the persistent pines.

Table 7. Statistics of the overall PI values (all dates considered).

	Potential	*Permanent*	*Intermittent*
Mean	1.065	1.018	1.096
Standard Deviation	40.920	37.596	42.935
Kurtosis	15.912	9.533	17.938
Skewness	-0.097	0.29412	-0.26743
Minimum	-794.6	-495.49	-794.6
Maximum	784.77	473.84	784.77

4.4 *Assessment of carbon pooling areas*

Assessment of the trends of change in carbon stocks was feasible by exploring density homogeneous landscape units. The PI values of homogeneous elements defined in 2000 with the TCA (forest density proxy) are normally distributed, with a mean value very close to zero on all dates (figure 7) and standard deviation around 40 (table 7). As expected, the distribution is narrow on initial dates, with a low variance of PI; the variance increases steadily before 1991 and more notably later. The global stability of the landscape carbon stocks decreases progressively (figure 7) during the period of analysis: areas with relatively steady carbon stocks (i.e. not modifying forest density) at initial dates develop towards higher carbon stocks (e.g. density increment) or lower (e.g. density drop) carbon stocks.

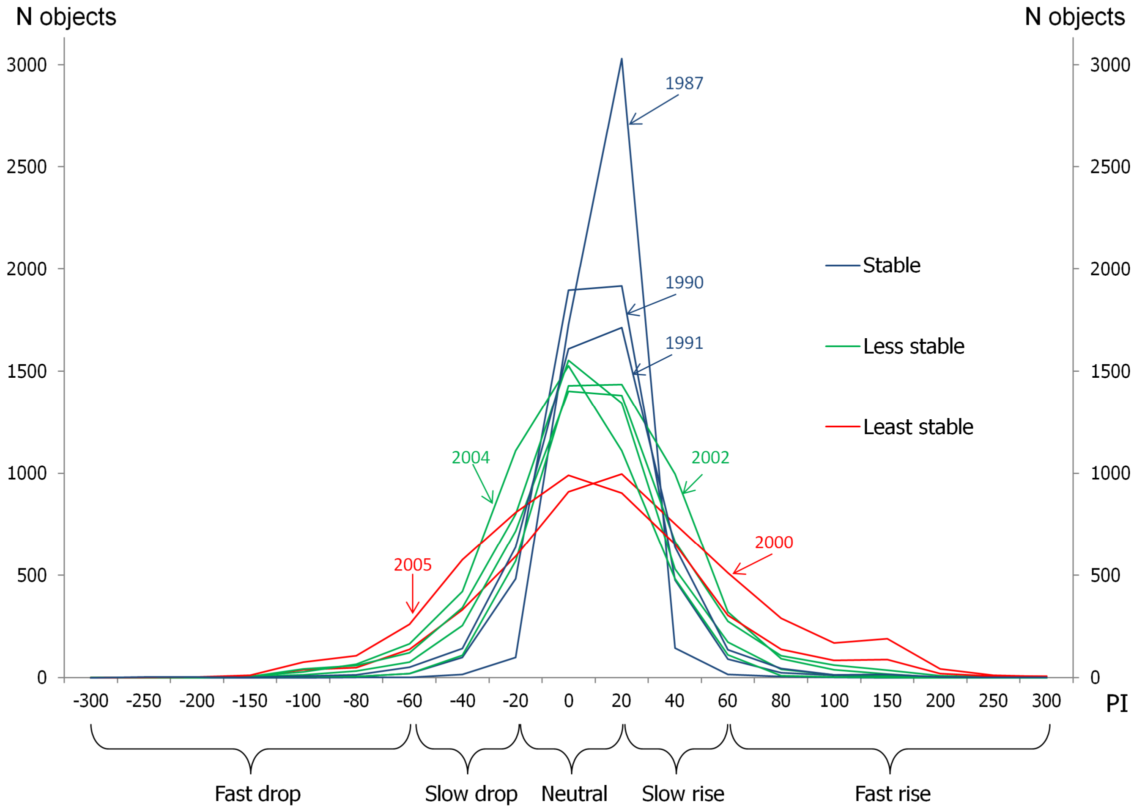

Figure 7. Distribution of MPPA 2000 objects' PI values at different dates.

To facilitate interpretation of these results, and to produce more detailed information on the spatial distribution of carbon pooling changes over time, we established five categories of PI values, based on the statistical distribution present (figure 7, table 8). The carbon stock of objects in the *neutral* group is not in a process of change; the *slow drop* and *slow rise* groups are in a slow process of changing their carbon stock towards lower or higher levels, respectively, and the *fast rise* and *fast drop* groups are in a relatively rapid process of changing their carbon stock towards higher or lower levels respectively. The scene specific character of the PI values produces results relative to the area; comparison with results in other areas would require thorough calibration of values.

Table 8. Classification of PI values in carbon stocking classes. Groups are defined based on statistical distribution criteria.

	PI	Carbon stocking process	Simplified class
1	<-60	Fast drop	Drop
2	-60 to -20	Slow drop	
3	-20 to 20	Stable	Neutral
4	20 to 60	Slow rise	Rise
5	>60	Fast rise	

All segments were classified at each date in one of these five categories (table 8); the number of objects and the area in each of the carbon pooling groups at each date was assessed. On average there was 64% of the area in a *neutral* carbon pooling process over the entire period (figure 8(*a*), table 9). The maximum area in this process group occurred in 1987 (96% of total area) and the minimum in 2005 (40% of total area). The *neutral* area followed a consistent lowering trend over time (figure 8(*b*)). On average, only 2% of the *potential* area was in *fast rise* and a similar 2% of the area was in *fast drop* carbon stocking processes during the period (table 9). *Slow rise* and *slow drop* carbon stocking processes represent equivalent areas along this period, with an overall average of 17% and 15% respectively (table 9).

Table 9. Area proportion of carbon stocking groups.

Process	***1987***	***1990***	***1991***	***2000***	***2001***	***2002***	***2003***	***2004***	***2005***	***Average***
Fast Rise	0.06	0.21	0.50	9.11	1.62	0.29	0.50	2.13	4.04	2.05
slow rise	2.31	8.19	12.96	24.05	23.44	12.84	18.00	15.10	15.87	14.75
RISE	2.37	8.40	13.47	33.16	25.06	13.13	18.50	17.23	19.91	16.80
Neutral	96.37	82.91	72.39	44.36	62.08	57.43	60.03	62.62	40.05	64.25
slow drop	1.24	8.48	13.64	19.51	12.63	26.65	18.66	18.80	32.58	16.91
Fast Drop	0.02	0.22	0.50	2.97	0.23	2.79	2.81	1.35	7.46	2.04
DROP	1.27	8.70	14.14	22.48	12.86	29.44	21.47	20.15	40.04	18.95
NET ACTIVE (RISE—DROP)	1.1	-0.3	-0.67	10.68	12.2	-16.31	-2.97	-2.92	-20.13	-2.15

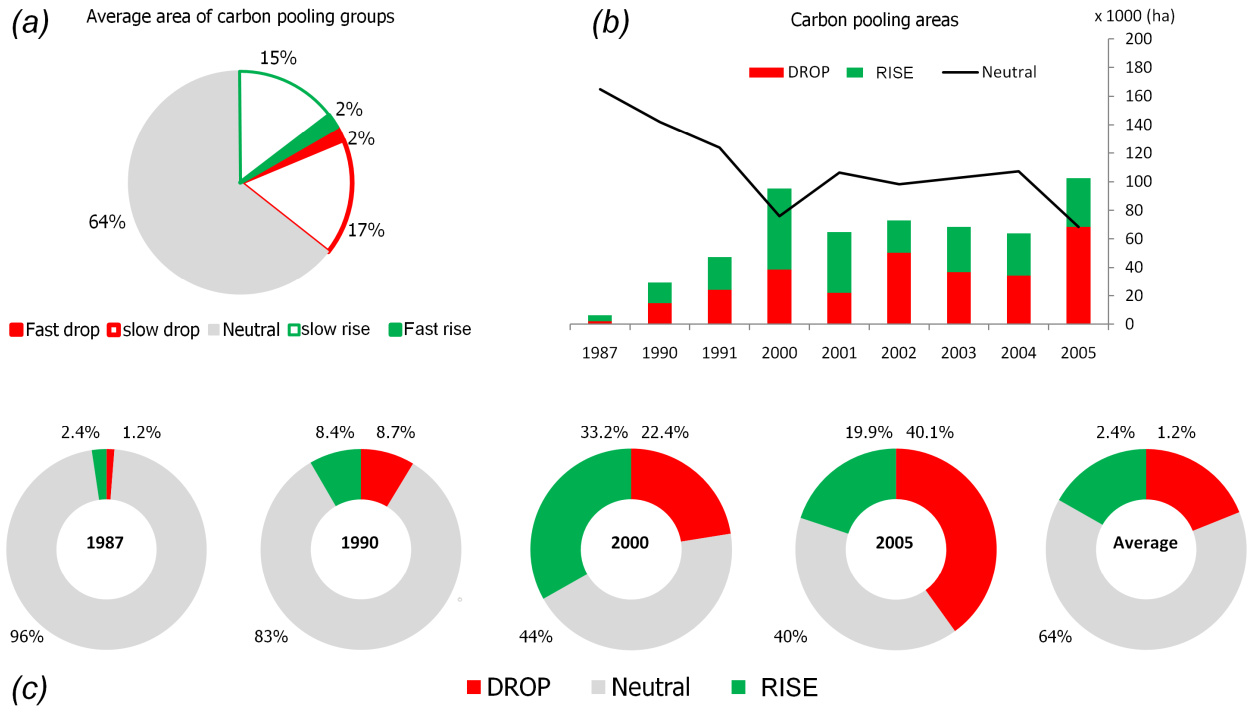

Figure 8. Proportion of carbon stocking groups. (a): average percentage over the whole period; (b): evolution along the period; (c): proportions at various dates and overall average proportion.

Because the *fast rise* and *fast drop* categories made up very small proportions, we considered a more simplified classification in further description: rise, neutral and drop are the three categories considered (table 8). *Neutral* is the area maintaining the carbon stock without significant change, and as mentioned before, it was diminishing over time to balance an increasing activation of carbon pools (figure 8(*b*)): larger areas were progressively entering processes of rising or dropping carbon stock.

Before 2000 more than 70% of the MPPA area was *neutral* and after that it fluctuated between 40 and 64%. The area in a process of rising carbon stock reached a minimum proportion in 1987 (2%) and a maximum proportion in 2000 (33%). The area in process of dropping carbon stock reached a maximum proportion in 2005 (40%) and a minimum in 1987 (2%). The area fractions in different categories of carbon stocking process at various dates are shown in figure 8(*c*).

4.5 *Intermittent and permanent areas carbon pooling*

In order to determine whether the area permanently covered with pine and the area only intermittently covered follow similar carbon pooling trends during the time studied, these areas were analysed separately. We found that the *neutral* area—stands in which carbon stock is not changing appreciably—follow a linear decreasing trend in both areas, although more pronounced in the *intermittent* area (figure 9(*a*)). The *permanent* area has a more equitable distribution of areas in the process of rising and dropping carbon stocks, with distributions only out of the 30-70 range on two occasions (2003 and 2005, figure 9(*b*)). The *intermittent* area shows relatively equitable distribution of areas in the process of rising and dropping carbon stock, except in the initial years of the last decade, when distributions reached the 80-20 range.

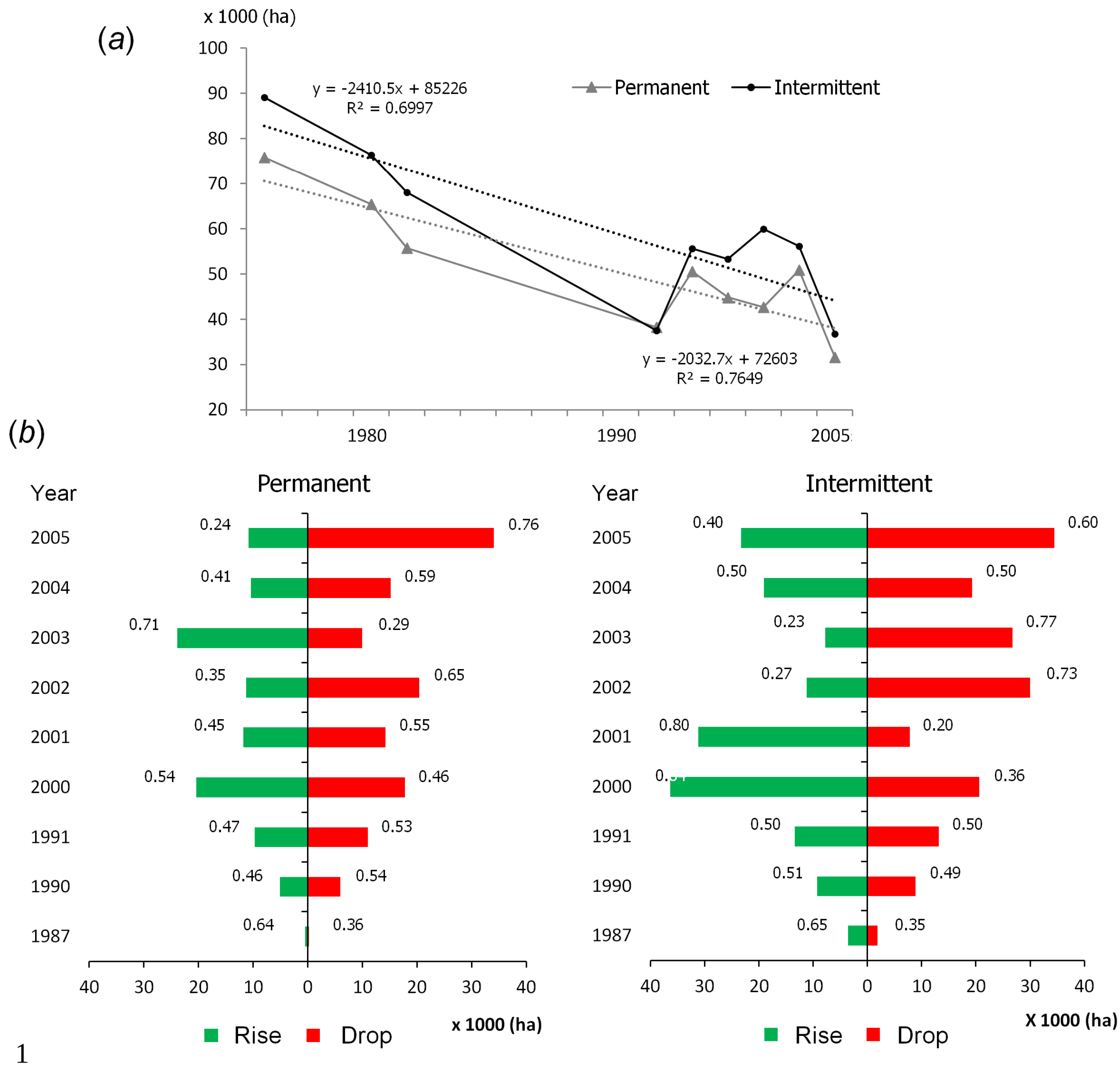

Figure 9. Evolution of carbon stocking areas. (a): the neutral carbon stocking area shows a clear tendency to diminish; (b): rise and drop in Permanent and Intermittent areas. Percentage values of change are indicated next to the bars.

Observing the enlargement of area ongoing processes of rising or dropping carbon stock, it is clear that a carbon pooling activation has occurred in the last 25 years. Designated as *active* area in figure 10, the changing area shapes a trend complementary to *neutral* (figure 9(*a*)). Rising and dropping areas have been compensated for, driving the *net* area chrono-line very close to zero (figure 10). Contributions of the *permanent* and *intermittent* regions are shown.

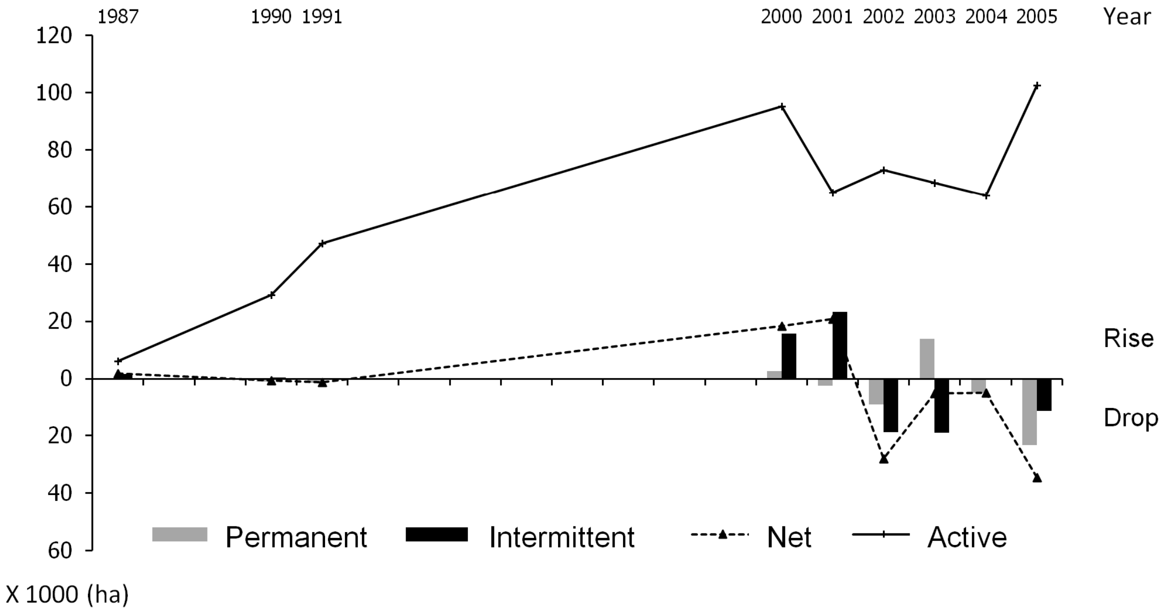

Figure 10. Carbon stocking net area. (Net = abs(rise – drop)).

5. Discussion

Variations in the area and distribution of pines occurred during the last 25-year period in the Central Range of Spain were assessed with a multilevel object-based classification of normalized images acquired at regular intervals. Further, the time series of Landsat images and two spectral indices derived from the TCT enabled description and analysis of changes in carbon stocking pools. The TCA is strongly correlated with forest stand density in the study area, and its derivative, the PI, characterizes rates of changing processes. Results indicate that the pine dominated area in the Central Range has increased by 40% from the initial to the final date; there is an area permanently covered with pines and a large extent only temporarily occupied during these decades. Carbon stocking pools have been activated in the second half of the analysis period, when larger areas show faster rates of rise and fall of carbon stocking.

Land use in the study area is governed by national and regional administrations, and land use changes do not proliferate. Moreover, pines in the Central Range have been managed in a sustainable manner for several decades (Bravo *et al.* 2010), with extractions of light intensity and assurance of regeneration by natural methods or plantation; clear cutting is not a local forest management practice. We expected small variations of *pine* area during the 25 year period of analysis, except in sporadic fire disturbed areas. The approach applied for land cover classification is based on objects with contextual information (Johansen *et al.* 2010) and includes the TCA among the input features to aid in sorting stand density. Thanks to the multilevel character of each date classification, simultaneous detection of larger stands with the required characteristics (species and density) and undersized objects in patchy areas was possible; this technique is of particular interest in distinguishing smaller changes in distribution that would otherwise blur into larger objects or be rejected as a speckle effect in a pixel-based classification.

Class signatures from samples in the reference image (date 2000) were used to classify other images (date 1984, 1990, 2009) assuring identical classification criteria. For assessment of classification accuracy, the independent reference information required (Congalton and Green 1999) was only available for one date; we relied on the exhaustive process of radiometric normalization and assumed similar accuracy in other classifications (accuracy > 90%). One of the difficulties when comparing the Spanish NFI data for assessment of change is the declared disparity of base cartography used in each repetition (Vallejo 2005). With a historical series of good quality images available, retrospective studies of change become feasible and offer increased precision. In this work we classified images acquired at time intervals similar to NFI repetitions (10 years), and our results are in agreement with other studies based on field data comparison (i.e. indicating a trend of increment in forest area). The spatially detailed information provided and the capacity to readily incorporate data at intermediate dates for more detailed reports are some key strengths of methods based on remotely sensed data.

Obtaining reference independent information with sufficient temporal frequency for validation of change maps is complicated (Lu *et al*. 2004, Cohen *et al*. 2010). Visual validation of changes was possible in the eastern area (Madrid province) where online historical aerial photography is available (http://gestiona.madrid.org) at varying time steps. We could readily corroborate the spatial location of change events, but the exact time of occurrence was more complicated, especially when the time step of our series of images differed markedly from the reference data; subtle changes could only be visually compared. The decadal frequency of typical field data is insufficient for the validation of frequent change maps. Further, more work is needed in developing methods for the evaluation of historical change accuracy; some strategies incorporating high spatial resolution images are emerging, like the TimeSync tool from Cohen *et al*. (2010), which incorporates imagery from Google Earth. Although this is an invaluable source of data, GoogleEarth images are only available for a short historic period and the global coverage is not complete with a sufficiently dense frequency, making designed-based methods (Thomas *et al*. 2011) the most feasible option for our situation in central Spain.

The TCA index is relatively new, but the relation of greenness to brightness components of the TCT for characterizing forest density classes and successional stages has been used before in various forest environments. In our study area the TCA is strongly related to forest density; with three or more consecutive images the PI enables the characterization of relative rates of change in forest density and carbon stocks. TCA and its derivative, the PI, resulting from the TCT, are scene dependent (Crist and Cicone 1984). Possible artefacts induced by annual phenology dissimilarities are minimized by a rigorous process of normalization. We analysed trends in carbon stocking for the MPPA (area potentially covered by *pine* during the whole period) and assessed rates of change, comparing the area permanently covered with pines and the area intermittently covered. There is a trend towards activation of carbon pools, but *intermittent* area shows higher variability of processes and the area of permanent pine confers a more neutral carbon pooling character. We focused our analysis on change processes, but a combined interpretation of the TCA and its derivative, the PI, can provide a simultaneous view of forest density and change processes going on, thereby enabling some understanding of the elusive relationships between landscape patterns and processes—a recursive question of landscape ecology. Further work to calibrate the TCA values with quantitative density estimations is recommended to permit a simultaneous characterization of patterns and processes.

The PI continuous scale of values provides versatility in change detection capacity and enables the characterization of rapid (high PI values) and slow (low PI values) rates of change. With an adequate time interval between images, subtle changes in forest density can be detected; this is of particular interest in the Mediterranean area, where the majority of forests are subject to some drought and are relatively slow growing compared with other temperate areas (Merlo and Croitoru 2005). In managed forests, partial harvest or thinning operations might be detected (low negative PI value) and later recovery of density tracked (positive PI value). If the silvicultural goal is to maintain a constant value of BA, a time series of PI values would remain close to zero. Assessment of the absolute values of carbon sinks and sources remains an on-going question (Houghton 2003) but historic trends of relative carbon stock changes can be assessed, and the effect of management practices monitored with detailed spatial information. A PI based approach is especially informative for locations characterized by subtle, non-stand replacing disturbances.

6. Conclusions

The availability of a long time series of Landsat images offers an opportunity for retrospective historical studies of forest change. Temporally dynamic models relating spectral properties and forest structural condition facilitates the evaluation of changing trends. A relatively new index derived from the TCT, the TCA has supported the assessment of change in the area and distribution of Mediterranean pines in Central Spain for a 25 year period. Although absolute values of carbon fluxes were not assessed, characterization of changing trends in relative carbon stock was assessed with the *Process Indicator* (PI), the TCA derivative, and further characterized by subperiods of time, with subtle change detection also enabled and demonstrated. The spatial definition of sources and sinks as well as changing trends over time are a valuable contribution for the global issue of carbon budgeting reports and for evaluation of management strategies.

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