Assessment of degraded forests supported with UAV imagery towards planning rehabilitation strategies.

Case study in the Argentinian Yungas

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Abstract

To assess and rehabilitate degraded forests are global challenges. Due to the various causes and severity of degradation, they typically show a very diverse structure, which makes acquiring a detailed inventory, as a first step toward rehabilitation measures, difficult and costly. Area-based inventories based on satellite imagery are a well-established methodology to assess and classify the forest cover, but the information obtained is often not detailed enough to fulfil the needs of site-adapted rehabilitation in degraded forests with a highly diverse structure. Furthermore, due to the great variability of the forest structure, a great number of ground sample plots are necessary to establish statistically sound predictions of structural parameters.

New technologies, such as unmanned aerial vehicles (UAV), allow the acquisition of detailed images, but until now they are mostly used to estimate forest attributes only in small scale applications, and if a precise digital terrain model (DTM) is available, since optical sensors cannot sense terrain under dense canopy covers. However, the frequent canopy gaps on degraded forests would allow the partial assessment of the terrain, and the combination of wall-to-wall satellite imagery with partial cover UAV imagery would allow larger scale inventories of acceptable accuracy and reliability without the need for an increased number of ground sample plots. This approach was developed and tested in this research, and applied to a 3944 ha case study in the Argentinian Yungas Cloud Forest (named Florestoona), which was degraded by a mixed-severity fire in 2013.

Therefore, as a first objective, this research assesses whether or not the inclusion of partial cover unmanned aerial vehicle imagery could reduce the classification error of a SPOT6 image used in an area-based inventory of a forest affected by a mixed-severity fire. Basal area (BA) was calculated from ground inventory and was used to run a first classification of the satellite image (BA-based classification). Then, BA was correlated to partial canopy cover and different tree heights, calculated from AUV imagery derived canopy height models (CHMs), in order to formulate the adjusted canopy cover

index (ACCI) and run a second image classification (ACCI-based classification). The ACCI-based classification did not improve the classification error in comparison with the BA-based classification, but it achieved more homogeneous strata, since the inclusion of forest structure parameters derived from AUV imagery allow to correctly classify stands which have similar reflectance but are very different in regard to their structure and stock. Additionally, two resolution DTMs were used to calculate CHMs, which were assessed against measurements in the field at different degrees of forest degradation. CHMs underestimated tree height with a root mean squared error (RMSE) ranging from 2.8 to 8.3 m, having the most accurate estimation with lower resolution DTMs (10 m/pixel) and more degraded forests.

Once a detailed map of the degraded forest was available (stands of 3.129 m^2 on average were delineated), it was the second objective of this research to establish meaningful forest management units (FMU) in order to plan and implement forest rehabilitation measures. FMUs should be big enough to facilitate operations, but also homogenous on forest structure and stock so that uniform adapted rehabilitation measures could be applied. The aim was to develop and demonstrate a method to establish meaningful FMUs based on the spatial distribution of ACCI values as a metric of forest structure and stock. Therefore, close and similar features were clustered through the use of the tool Hot Spot Analysis (Getis-Ord Gi*) from the environment Arc-GIS. Clustering on a multi-scale analysis was conducted to test spatial autocorrelation on neighbouring areas of 10, 20, 30 and 40 ha, resulting in threshold radii of 178, 252, 309 and 357 meters, respectively. The tool demonstrated to significantly aggregate between 30.7 % (at 178 m) to 60.8 % (at 357 m) of the area into either cold or hotspots, which would be the basis to delineate FMUs, where adaptive rehabilitation measures can be planned. In the remaining areas, the structural parameters were randomly distributed, thus a conventional approach to identify FMUs by expert knowledge should be applied. The results reported a trade-off between the gain in area of the FMUs and the loss of their homogeneity. The incorrectly clustered area increases from 7.1 % to 19.1 %, from 178 to 357 m distance thresholds.

Furthermore, in this dissertation, adaptive rehabilitation strategies for each type of FMU (with concentration of high, low, and randomly distributed ACCI values) are analysed and discussed based on the result obtained from a ground inventory carried out on enrichment planting (EP) experiments established since 2004 in Florestoona. The experimental plots were planted without specific statistical design, with the species *Toona ciliate* M. Roem., *Melia azedarach* L., and *Tipuana tipu* Kuntze. The results reported that the species would need a rotation of 15, 10, and 20 years respectively, in order to reach 40 cm DBH, which is the diameter of harvest. However, those results overestimate the performance of the EP since due to the line or strip design of the EP, up to 80 % of the EP areas are considered as border areas where, due to edge effects, growth is lower than in the core, where the measurements took place.

Finally, for a partial area of Florestoona, detailed recommendations for implementing adapted rehabilitation measures in selected FMUs are given as an example based on the findings of this research, and on an extensive literature review about the origins and actual implementation of EP in the region. It shows how the concepts and methods developed and applied in this research can support the practical implementation of adapted rehabilitation measures.

Zusammenfassung

Fotooptische Erfassung der Strukturen von degradierten Wäldern unten Einsatz von Drohnen für die Planung von Rehabilitationsmaßnahmen.

Fallstudie in dem argentinischen Yungas.

Fernando C. Rossi

Degradierte Wälder machen weltweit einen zunehmenden Anteil der noch verbleibenden natürlichen Waldflächen aus. Ihre Rehabilitation ist eine globale Herausforderung. Wegen der Vielzahl der Ursachen und der verschiedenen Intensitäten ihrer Degradation zeigen diese Wälder zumeist komplexe und oft kleinräumig diverse Strukturen. Dies erschwert und verteuert die als Voraussetzung angepasster Rehabilitationsmaßnahmen notwendigen Inventuren. Satellitengestützte auf größere Gebiete bezogene Inventuren bieten gute Möglichkeiten, den Waldzustand zu erfassen, jedoch sind die generierten Daten häufig nicht detailliert genug, um die in degradierten Wäldern kleinräumigen Strukturen zu erfassen und standort- und bestandesspezifische daran angepasste Rehabilitationsmaßnahmen festlegen zu können. Zudem wäre eine sehr große Anzahl an Probeparzellen im Bestand nötig, um statistische relevante Ergebnisse zu erzielen.

Moderne Technologien, wie z.B. Drohnen, ermöglichen die Aufnahme detailreicher Luftbilder. Der Einsatz in der Forstwirtschaft beschränkt sich aktuell eher auf kleinflächige Einsatzgebiete und setzt das Vorhandensein eines hinreichend aufgelösten digitalen Geländemodells voraus, da die optischen Sensoren dichte Baumkronen nicht durchdringen können. Die häufigen Lücken im Kronendach degradierter Wälder könnten jedoch eine Erfassung der Geländeoberfläche zum Teil erlauben. Zusätzlich könnte die Kombination von „wall-to-wall" Satellitenaufnahmen mit Luftbildern, aufgenommen durch Drohnen großflächige Inventuren mit höherer Qualität ermöglichen, ohne den Stichprobenumfang von Probeflächen im Bestand zu erhöhen. Gerade unter den Bedingungen entlegener, großflächig degradierter Waldgebiete in tropisch-

subtropischen Regionen mit begrenzter Verfügbarkeit von verlässlichen Geodaten, aber auch von aufwendiger Lasertechnologie, wäre dies von großem Vorteil.

Dieser Ansatz wurde im Rahmen einer Fallstudie in einem 3,944 ha-großen, durch partielle Übernutzung und Feuer im Jahr 2013 degradierten Waldgebiet in der NW-Argentinischen subtropischen Yunga-Waldzone entwickelt und beispielhaft umgesetzt.

Als erste Zielsetzung wurde evaluiert, ob sich durch das Einbeziehen von partiellen Drohnenaufnahmen die Klassifizierungsfehler von SPOT6 Aufnahmen als Eingangsdaten von gebietsbezogenen Inventuren in durch Waldbrände mittlerer Stärke degradierten Wäldern reduzieren lässt. Aus bodengestützten Inventurdaten wurde die Bestandesgrundfläche ermittelt und mit dieser die Satellitenaufnahmen strukturiert und nach dem Grad der Degradation durch Feuer klassifiziert. Anschließend wurden mittels der Kronenhöhenmodelle (canopy height model – CHM), mit den Drohnenaufnahmen als Eingangsdaten, der Kronenschluss (Überschirmungsgrad) und die Baumhöhen bestimmt und mit der Grundfläche korreliert, um einen höhenkorrigierten Kronenschluss Index (adjusted canopy cover index – ACCI) zu generieren. Auf dieser Grundlage wurde danach eine verbesserte zweite Klassifizierung berechnet. Im Vergleich zu traditionellen Inventurmodellen (ohne Drohnenaufnahmen) wurde damit zwar keine Verringerung des Klassifizierungsfehlers insgesamt erreicht. Die berechneten Straten waren jedoch viel homogener, da die Drohnenaufnahmen eine Differenzierung nach Bestockungsgrad und Strukturvielfalt ermöglichen, im Gegensatz zu Satellitenaufnahmen, mit denen Bestände nach dem Reflektionsgrad der Vegetationsoberfläche klassifiziert wurden, was vor allem bei niedrigem Bewuchs (Lianen, Büsche) zu Klassifizierungsfehlern führte. Da kein digitales Geländemodell (DTM) mit ausreichender Auflösung vorlag, wurden außerdem aus den Satelliten – und Drohnenaufnahmen Geländemodelle mit zwei unterschiedlichen Auflösungen generiert und zur Herleitung des Kronenhöhenmodells CHM verwendet und mit den Baumhöhendaten der bodengestützten Inventur verglichen. Die Baumhöhen wurden dabei durch das CHM unterschätzt, da die optischen Sensoren der Drohnen nicht überall zur Geländeoberfläche durchdringen können. Die präzisesten Höhenwerte wurden mit dem DTM mit geringerer Auflösung (10 pixel/m) und in stark degradierten Situationen erzielt.

Das Ergebnis der Klassifizierung war ein sehr kleinflächiges Mosaik von unterschiedlich strukturierten Beständen (Durchschnittsgröße 3.129 m^2). Für die praktische Umsetzung von Rehabilitationsmaßnahmen, wie z.B. Anreicherungspflanzungen (Enrichment Planting - EP) sind größere Abteilungen (Management Units FMUs) unabdingbar. Diese werden bisher zumeist auf Karten gutachtlich-visuell ausgeschieden. Angesichts der vorhandenen detaillierten Strukturinformationen war es ein zweites Ziel dieser Arbeit, aus diesem Mosaik von Einzelbeständen auf quantitativer Grundlage FMUs zu generieren, die einerseits groß genug sind, und anderseits in Bezug auf ihre Struktur (hier gemessen als ACCI) hinreichend homogen sind, um in der Praxis einheitliche Rehabilitatiosmassnahmen umzusetzen. Dazu kam eine Methode der Clusterung (Hot Spot Analysis Getis-Ord Gi*) zur Anwendung. Diese Methode clustert Flächen, die in einem bestimmten Abstandsradius liegen und hohe ACCI Werte aufweisen, als hotspots und solche mit niedrigen ACCI Werten als coldspots. Aufgrund örtlicher Erfahrungen wurden beispielhaft vier alternative Abstandsradien gewählt, die FMU-Flächen von 10, 20, 30 und 40 ha entsprechen. Die mit signifikantem Ergebnis als hot- oder coldspots klassifizierten FMUs aggregierten zwischen 31% und 61% der Gesamtwaldfläche, je nachdem ob der kleinste (178 m) oder der größte (357m) Abstandsradius vorgegeben wurde. Dabei ist ein trade off zwischen FMU-Größe und -Homogeneität zu beobachten: Wird 357 m als Radius gewählt, steigt der Anteil fehlerhaft aggregierter Bestände gegenüber FMUs mit 178 m Radius von 7,1 % auf 19,1 % Flächen-prozent an. Die verbleibenden Flächen weisen eine zufällige (random) räumliche Verteilung von Beständen mit unterschiedlichem ACCI auf, sodass keine Clusterung mit signifikantem Ergebnis möglich ist und sich damit eine einheitliche waldbauliche Behandlung nicht anbietet.

Dritte Zielsetzung der Arbeit war es, auf der Grundlage der Klassifizierung und der nachfolgenden Clusterung in FMUs beispielhaft konkrete Vorschläge für eine nach dem Grad der Degradierung differenzierte waldbauliche Behandlung der degradierten Waldfläche des Fallstudienbetriebes zu entwickeln, wobei der Schwerpunkt bei der Anreicherungspflanzung (Enrichment Planting - EP) als der aufwendigsten Behandlungsmethode lag.

Dabei berücksichtigt werden sollten bisherige waldbauliche Erkenntnisse und Erfahrungen mit EP aus dem Beispielsbetrieb und aus der Region, aber auch rechtliche, z.B. umweltschutzbezogene Begrenzungen und Rahmenbedingungen für eine finanzielle staatliche Förderung von Rehabliationsmaßnahmen. Die Analysen und ihre Ergebnisse werden für einen Ausschnitt des Fallstudienbetriebs detailliert dargestellt, und können als Muster für ein Vorgehen unter vergleichbaren Voraussetzungen dienen.

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List of abbreviations

ACCI	Adjusted canopy cover index
ALS	Airborne laser scanning
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible/Infrared Image Spectrometer
BA	Basal area
CC	Canopy cover
CerFoAr	Argentine Forest Certification System
CHM	Canopy height model
CHM5	Canopy height model calculated from DTM5
CHM10	Canopy height model calculated from DTM5
COFEMA	Consejo Federal del Medio Ambiente
CS22	CONEFOR Sensinode 2.2
DBH	Diameter at breast height
DSM	Digital surface model
DTM	Digital terrain model
DTM5	Digital terrain model with 5 m /pixel of resolution
DTM10	Digital terrain model with 10 m /pixel of resolution
DMC	minimum diameter of cutting
EP	Enrichment planting
EEA	experimental station
ETM+	Enhanced Thematic Mapper
FAO	Food and Agriculture Organisation of the United Nations
FCT	future crop tree
FDR	False Discovery Rate
FMU	Forest Management Units
FSC	Forest Stewardship Council
GO	Governmental organisation

GV	Green Vegetation
HCV	high conservation values
IIC	Integral Index of Conectivity
IRAM	Argentine Institute for Normalisation and standardisation
INTA	Instituto Nacional de Tecnología Agropecuaria (National Institute of Agricultural Technology)
ITTO	International Tropical Timber Organization
MAGyP	Ministerio de Agroindustria de la Nación Argentina (Ministry of agro-industry of Argentina)
MAE	Mean absolute error
MAI	Mean annual increment
MTBS	Monitoring trends of burn severity
NDVI	Normalised Difference Vegetation Index
NGO	Non-governmental organisation
NIR	Near infrared
NOA	North-western Argentina
NOAA	National Oceanic and Atmospheric Administration
NTFP	non-timber forest products
OS	Operating system
P&C	Principle and criteria
PEFC	Programme for the Endorsement of Forest Certification
RGB	Red-Green-Blue
RS	Remote sensing
SAyDS	Secretaria de Agricultura y Desarrollo Sustentable de la Nación Argentina (Secretary of Agriculture and Sustainable development of Argentina)
SB	Severely burned
SE	Standard error

SFM	sustainable forest management
SfM	structure from motion
SRTM	Shuttle Radar Topography Mission
THC	Tree height class
THC1	CC from trees height between 5 and 10 m
THC2	CC from trees height between 10 and 20 m
THC3	CC from trees higher than 20 m
TIN	Triangular Irregular Networks
TIRS	Thermal Infrared Sensor
UAV	Unmanned aerial vehicle
VSB	Very severely burned

1 Introduction

The rehabilitation of degraded forests is a global challenge for both science and practise. Therefore, several international commitments focus on the restoration and rehabilitation of degraded forest lands (Stanturf et al. 2017). Frolking et al. (2009) claimed that every year between 40 and 70 million hectares suffer abrupt disturbances due to fire, windstorms, logging and shifting cultivation, among other reasons. The authors of Simula & Mansur (2011) claim that 2,000 million hectares are degraded and are potential goals for restoration and rehabilitation worldwide. The Global Partnership on Forest Landscape Restoration, according to the Bonn Challenge, expect 150 million hectares to be restored all around the world by 2020 (Laestadius et al. 2011).

Forest degradation is particularly concentrated in developing countries (Simula & Mansur 2011), where reliable information on forests, and also the resources to obtain them, are scarce. In Argentina, forest degradation has often been addressed by scientists, but still not assessed at a national scale. The most important causes of degradation in this country are grazing, illegal logging, fire, and extensive logging (FAO 2009). With the aim of limiting the degradation, and to rehabilitate degraded forest areas, in 2007 the Argentinian Government launched the national law 26331 `for the protection, enrichment, conservation, rehabilitation, use and sustainable management of native forests. Degraded forests are, in terms of the regulation of this law (decree 91/2009), those forests which have lost structure, functions, species compositions and productivity in comparison to the original forest ecosystems. This law offers economical support for rehabilitation activities by enrichment planting, aiming at increasing the participation of desired natural species in the forest composition.

In the north-western Argentinian Yungas Cloud Forest, the definition and delineation of degradation of forest lands is particularly difficult due to their complex structure (Malizia et al. 2012). Furthermore, additional diversification is created in mortality-patch size, species composition, and post-fire dynamics of surviving trees with fire-created coarse wood, when forests are affected by mixed-severity fires (Dunn & Bailey 2016). Forests affected by mixed-severity fires show a heterogeneous spatial distribution of high, moderate, and low severity (Penman 2003). Furthermore, forests in Northwestern Argentina show additional diversification and degradation due to illegal logging. Due to a deficit of wood supply in this region, a big proportion of the timber from native species comes from illegal trade (INCOTEDES 2014). Restoration efforts, with focus on future sustainable utilisation, would consequently decrease the human pressure on native forests, and would be beneficial for the development of the local and regional wood industry, which today faces a deficit in wood supply (Ministerio de Ambiente y Desarrollo Sustentable de Salta 2009; Paredes 2013).

In order to characterise and quantify degraded forests, and to develop rehabilitation strategies, it is necessary to establish degradation indicators, including quantitative definitions and thresholds. Thompson et al. (2013) proposed that more than one indicator should be taken into account to measure stand heterogeneity. When identifying thresholds of forest degradation, the local definition of forest should be taken into account. The Argentinian Federal Council of Environment (Consejo Federeal del Medio Ambiente 2012) has set minimum thresholds of extension (0.5 ha) and canopy cover (20 %) of certain tree heights (3 m; Consejo Federeal del Medio Ambiente 2012) for a land to be legally considered a forest. Forest canopy cover (CC) and tree height are also of great interest for the prediction of basal area (BA), which is a widely used variable to measure stock and productivity of a forest, and has been used to assess differences in forest structure after mixed-severity fires (Dunn & Bailey 2016).

Attempts to assess the structure of degraded forests have been made with different satellite sensors (Asner et al. 2002; Souza et al. 2005; Dennis & Colfer 2006; Matricardi et al. 2010). IKONOS high-resolution satellite imagery is an important technological development used to evaluate damage on CC by logging and fire, without using aerial imagery (Souza & Roberts 2005; Herold et al. 2006). Fire damage has already been assessed at large and local scales by the use of other satellite imagery (Kasischke & Turetsky 2006; Chuvieco & Kasischke 2007). However, those approaches have their limitations with respect to possible ground resolution, frequent cloud cover, and costs of obtaining the imagery (Souza & Roberts 2005; Anderson & Gaston 2013). Consequently, Frolking et al. (2009) remarked that key hurdles from the use of satellite imagery have to be addressed. More recently, several researches (Dandois & Ellis 2010; Wallace et al. 2012; Lisein et al. 2013; Nurminen et al. 2013; White et al. 2013; Penner et al. 2015) have compared results of predicted forest structure attributes from Airborne Laser Scanning (ALS) and Unmanned Aerial Vehicle (UAV) imagery. However, when using UAV imagery, a precise digital terrain model (DTM) was used, since photography does not allow a precise assessment of ground under dense canopy for calculating a photogrammetric DTM (Nurminen et al. 2013).

All present methods to map forests by remote sensing (RS) need a validation of the data with a ground inventory, since the most accurate information can be achieved with the combination of the two methods (Gerrand et al. 2011). Area-based inventories combine high-resolution, wall-to-wall, remotely-sensed data with sampled ground information in order to predict forest attributes over the whole area (Næsset 2002; White et al. 2013). A precise classification of a highly heterogeneous forest land, as forests affected by mixed-severity fires are, would typically need a dense network of field surveyed samples to supervise satellite image classification with an acceptable accuracy. For those cases, a highly detailed and precise prior stratification of the forest area could contribute to reducing the number of necessary field inventory plots at a specific target error. Integrating partial cover UAV imagery could contribute to decreasing the classification error of the satellite image used in area-based inventories. That would be achieved by supervising wall-to-wall satellite image classification with forest variables derived from canopy height models (CHM) calculated from UAV imagery (Ene et al.

2016). This approach would address one of the biggest limitations of using UAV imagery, since it is only recommended for studies covering up to 1000 ha (Wallace et al. 2012; Puliti et al. 2017).

With high definition data from UAV imagery, accurate and very detailed maps can be achieved, but they may be far too small scale to be used directly as a spatial basis to implement technical management activities in the field. Therefore, the resulting maps might need further analysis and processing in order to establish meaningful forest management units (FMU). Traditionally, the establishment of an FMU starts with aerial images, in an iterative process where experts observe big changes in vegetation, slopes of terrain, and soil types, which help to define FMU (Oregon State University 2017). However, lately, algorithms of spatial statistics, such as hotspot analysis, have been used in geography and ecology. The algorithms allow the automatic identification and clustering of stands which are situated in a certain distance and show similar attributes (Nelson, Boots 2008; Noce et al. 2016; Fei 2010). In order to acquire spatial statistics, a distance threshold is necessary to assess if there is any pattern in the distribution of the analysed phenomenon (Getis & Ord 1992; Noce et al. 2016). For example, to measure landscape connectivity, a series of indexes were formulated based on the dispersal distance of the species of interest (Pascual-Hortal & Saura 2006; Saura & Pascual-Hortal 2007; Saura & Torné 2009). However, most of the researches of spatial analysis applied to ecology are based on arbitrary distance thresholds (Nelson & Boots 2008), since much knowledge of the ecosystem dynamics to establish an optimal distance threshold is necessary. In order to address this uncertainty, Noce et al. (2016) proposed to conduct a multi-scale approach with the tool 'Hot Spot Analysis (Getis-Ord)' available in the environment ArcGIS 10.3 (ESRI 2015) in order to define the adequate distance thresholds in terms of the results, although the selection of a criteria that could be defined a priori seems to be more proficient in further studies.

After the delineation of FMUs, rehabilitation measures adapted to the degradation of each FMU and to local site conditions must be implemented. With the aim that it could be sustainably managed in the future, a forest structure which is adequate in coverage, species distribution, and productivity, should be re-established. One of the practices that have been recommended in this context is enrichment planting (EP). It has been studied and implemented, in Argentina and other south American countries, over the last 60 years to restore overexploited tropical forests (Dawkins 1961; Lamprecht 1990), but unfortunately without much success in practice so far (Gomez et al. 1996; Gomez & Cardozo 2003; Brassiolo & Gomez 2004; Noguera et al. 2006; Senilliani et al. 2006; del Castillo et al. 2011; Zulle et al. 2015).

Since 2007 in Argentina, EP is being supported economically under the National Laws 26331 (2007) and 25080 (1998), and therefore is receiving growing interest among forest managers, who were sceptic to implement it due to the lack of knowledge in the field. Consequently, new EP has been recently established in Northern Argentina. In 2008, there were 450 ha reforested under EP systems in the provinces of Salta, Jujuy and Tucumán (Balducci, 2009). In May 2016, for the same area, based on the official statistics of the Argentinean Government, there were 1,388 ha managed under EP (Ministerio de Agroindustria- Ministerio de la Nación Argentina 2016). However, there is a lack of information about the performance of EP experiences. Many cited researches are grey literature or conference papers. Also, most of them (as in the case of the present case study) were done in a trial-and-error approach, and no statistical design was used. Furthermore, the various EP designs, plantation spacing, species, and site conditions of the experiments make it difficult to identify the causes of their success or failure. Therefore, before suggesting adapted EP concepts in this research, an intensive literature review of the implementation of this practice in Argentina was carried out.

1.1 Objectives

In order to offer new tools for the assessment and rehabilitation of degraded forests, especially in remote areas without quality DTM, this research has three main objectives, which were addressed in a case study in the Argentinian Yungas Cloud Forest degraded by mixed-severity fires:

(1) to test and assess the usefulness of UAV imagery to complement satellite images in an area-based forest inventory of degraded forests. This includes the assessment of the quality of UAV imagery, DTM, and digital surface model, and the use of CHM-derived forest variables to supervise satellite image classification.

(2) to assess available tools to support the delineation of FMUs quantitatively; and

(3) to assess EP as an adapted rehabilitation measure, based on a review of the up to date implementation of EP in Argentina.

Specific objectives are:

- To identify attributes measurable by RS, which indicate forest degradation and are representative of the structure of the forest.
- To assess the precision of photogrammetric CHM across a gradient of fire-severity strata.
- To compare the classification error of the same SPOT6 image into fire-severity strata trained by two different input data: (1) BA from a ground inventory, (2) BA from a ground inventory, and CHM-derived forest variables calculated from partial cover UAV imagery.
- To assess the potential of the available tool 'Hot Spot Analysis (Getis-Ord Gi*)' for establishing FMUs using RS data from multiple small stands classified into strata of fire-severity.
- To propose a concept of EP adapted to different fire-severity strata for an example area in Florestoona.

2 State of the art

2.1 Forest degradation: definition and indicators

In order to stratify forests across a gradient of fire-caused degradation, first of all a definition and indicators of forest degradation have to be selected. However, it is a challenging task, since the concept of degradation has been widely discussed between scientists, practitioners and international institutions, but they have not yet agreed upon a worldwide accepted definition. For FAO (2009) a good definition of forest degradation should provide an appropriate set of indicators and variables to measure the change of a forest. However, FAO Global Forest Resources Assessment (FRA) limited its quantification on the FRA report 2010 (FAO 2010), and introduced a proxy indicator called 'partial canopy cover loss' (PCCL) in the FRA report 2015 (FAO 2015), but claimed its limitations due to the sub-pixel resolution in which degradation takes place.

In the present research, three definitions of forest degradation were selected as references to create an adapted concept to assess degraded forests in the Argentinian Yungas:

ITTO (2002): A degraded forest shows loss in the structure, functions, species composition, and/or productivity normally associated with the natural forest type expected at this site.

Griscom *et al.* (2009): Forest degradation is a direct, human-induced reduction in the forest carbon stocks from the natural carbon carrying capacity of natural forest ecosystems, which persist for a specified performance period and does not qualify as deforestation.

Penman et al. (2003): Forest degradation to be related to any direct human-induced long-term loss (persisting for *X* years or more) of at least *Y* % of forest carbon stocks (and forest values) since time *T* and not qualifying as deforestation or an elected activity under Article 3.4 of the Kyoto Protocol.

The survey carried out by FAO (2009) to assess the *status quo* of forest degradation around the world, shows that the main indicators used by the responding countries are growing stocks, forest/canopy cover, disappearance of biodiversity/species, occupancy/dominance of invasive/introduced species, erosion, wildlife habitats, and timber and non-timber forest products (NTFP) production/value. Lower ranked indicators include: soil fertility, species composition, areas affected by fire, fragmentation, presence of pioneer species/indicator species, and water quality.

Thompson et al. (2013) claimed that for the definition of thresholds to classify levels of forest degradation more than one indicator should be taken into account, and proposed a set of five criteria. Those criteria are: production, biodiversity, unusual disturbances, productive function, and carbon storage. The authors recommend to assess at least one from a set of indicators proposed for each criterion. That could be accomplished by ground assessment at management unit or landscape level or by RS, although improved precision needs data from the field. The authors have approached a way, but only at a conceptual level, to characterise forest degradation based on several indicators, although the selection of these indicators and thresholds are left for the stakeholders and managers.

An approach to an adaptive definition of forest degradation might consider the definition of forest and deforestation. A forest, which has faced a reduction of canopy cover under 10 % would be for ITTO (2002), a secondary forest. FAO (2009) claimed that it would be considered as deforestation. For UNFCCC this value must be set by each national government for its area. For Argentinian laws since 2012 (Resolution COFEMA 230), a forest must have a CC above 20 % for trees of a minimum height of 3 m, and must encompass a minimum area of 0.5 ha. From this definition, it can be assumed that forest degradation is an intermediate condition of the forest, which lays between fully stocked forest and deforested land. Therefore, CC has a key role, since it is a variable used by most of the international organisations to define deforestation and forest degradation. Furthermore, CC is a forest structure variable feasible to be estimated by RS, which can also be correlated to other variables for the prediction of forest attributes, such as forest stocks.

Furthermore, based on the second and third given definitions of degradation, it is necessary to set a timespan of the reduction of forest stocks in order to assess degradation. This time span should be coherent with the economical function of the forest, since, as stated by Lamb & Gilmour (2003), the rehabilitation of degraded forests (the goal of this research) aims primarily to recover forest structure and productivity in order to enhance its economical function. Therefore, and based on the operational objectives of this dissertation, the considered timespan is the rotation period of 20 years, which is established in the forest area for the management of multi-aged stands in the Yungas Cloud Forest (Balducci et al. 2012). If the present structure and stocks are considered insufficient to recover without intervention, rehabilitation measures must be taken to enhance its productivity. Consequently, the proposed definition of forest degradation to be used in this dissertation is as follows:

Degraded forests are those which show economic loss by the **reduction of their stock** and productivity; it implies **loss in their structure and functions,** resulting in a reduction of their capacity to provide goods and services **in a timespan of one rotation period or more**. The **forest cover must be above 20 %** for the forest land to be considered degraded and not deforested land.

2.1.1 Thresholds to define forest degradation

In order to apply the concept of forest degradation on area-based approach forest inventories, it is necessary to quantitatively define thresholds of forests degradation over selected forest variables. Even though the existence of thresholds for forest degradation is already accepted by the scientific community, it is defined only theoretically (Suding & Hobbs 2009; Thompson et al. 2013). Suding and Hobbs (2009) define thresholds as breaking points on the forest, in which small changes in environmental conditions would cause large changes on forests. When ecological systems are pushed over thresholds, they are vulnerable to irreversible changes, resulting in the loss of resilience (Lamb 1987; Pardini et al. 2010). On the other hand, those theoretical definitions find limitations to be applied for natural resources management, due to the complexity of factors and interrelations involved. Ideally, the definition of thresholds should be applied with a complete knowledge of the ecosystem's components and dynamics. However, sometimes a definition of numerical thresholds must be set arbitrarily in order to make decisions, even if a detailed knowledge of the ecosystem is not yet available.

Pattern-based knowledge, incorporating indicators, long-term monitoring, and expert knowledge may be the proper tools to evaluate and define thresholds for decision making (Suding et al. 2004). More feasible, but still time consuming, is the combination of pattern-based knowledge and modelling to define critical aspects for management activities (Groffman et al. 2006). Data collection to build long-term series are necessary for modelling purposes. That is one of the reasons why the definitions of restoration decisions are often solely expert knowledge based (Charron & Hermanutz 2016).

Additionally, multi-threshold models could help to lower the risk in cases where environment managers cannot afford long–term research to check on the environmental stability. The multi-threshold model presented by Suding & Hobbs (2009) defines two critical stages: a first one where only biotic components are modified and the intervention must be focussed on the biotic structure, and the second threshold in which the disturbance has affected the abiotic characteristics of the forest, and its degradation is irreversible without intervention on those components. Therefore, multi-thresholds could be applied for different levels of degradation on the biotic component, resulting in more than the two extreme classes: intact and degraded. Due to the lack of information about long-term dynamics, those thresholds should be flexible for further improvement when more and better knowledge of the forest becomes available. Therefore, it is necessary to set benchmarks for target forest management (Thompson et al.

2013; Morales-Barquero et al. 2014), which is the status of the forest before the degradation. The measured values of the chosen variable, compared to the benchmark, indicates levels of degradation.

2.1.2 Indicators of, and variables to measure forest degradation in Yungas

Based on the above proposed definition, **forest structure** and **stock** are the selected indicators to assess forest degradation in one rotation period, therefore variables to measure those indicators should be selected. Those variables should allow the definition of thresholds, which are specific enough for an ecosystem in order to accurately describe it, but flexible enough to be applied to different types of forests in future studies.

Thompson et al. (2013) recommend using a metric of the affected area as a variable for estimation of fire damage, and recommend measuring it by RS (satellite and aerial imagery). Gap sizes might also be a suitable variable to describe forest structure since, depending on the gap size, different species (shade-tolerant in small and shade-intolerant in larger gaps) will benefit (Pariona, 2003). The size of the gaps left in the forest after a disturbance (from selective logging to wildfire) dictates the distribution, amount, and type of available resources for colonisation e.g. sunlight, nutrients, and soil moisture.

Souza et al. (2005) estimated canopy damage caused by logging and fire in the Brazilian Amazon by the combination of green vegetation (GV), non-photosynthetic vegetation index and soil/shade fractions from Landsat Enhanced Thematic Mapper (ETM+) imagery. Souza & Roberts (2005) used visual interpretation of an IKONOS image to map forest degradation caused by logging and burning in the Brazilian Amazon, based on log landing sizes, canopy gaps, and the area of burned forest and forest regeneration.

Gerwing (2002) defined five classes of degradation level for 10 logged and burned forest areas in the eastern Brazilian Amazon, based on fire and logging histories of the stands, which were observed on the ground. He described each forest type based on ground cover composition, percentage of canopy cover, number of tree morphospecies in 0.5 ha, number of trees, saplings and climbing lianas per hectare, aboveground biomass, and total number of trees (dead and alive).

Dunn & Bailey (2016) conducted an area-based inventory to delineate and define forest degradation based on the Monitoring Trends of Burn Severity (MTBS) program of the USA. The MTBS classes of fire-severity are based on the difference Normalised Burn Ratio (dNBR) calculated over Landsat imagery, and establishes 4 classes of fire-severity (unburned, and low, moderate, and high severity). They found that the BA of low fire-severity stratum accounts for 60.2 % of the original BA in the forest, and the moderate fire-severity stratum with only 16.2 % of the original BA. The big difference between two adjacent strata shows the limitation of this approach, which is used primarily for estimation of fire-severity at national level, but it is not detailed enough for field level studies.

Fraser et al. (2017) studied the correlation of the dNBR with UAV-derived metrics and the Composite Burn Index (CBI) measured on the ground. The CBI measures fire damage on the ground based on five vertical layers. They correlated UAV and Landsat imagery derived spectral indices to predict CBI, as an indicator of fire-severity. However, they found better correlations comparing the indices they formulated from both remote sensors (UAV and Landsat imagery), than the correlation to CBI calculated from ground measurements.

MAGyP & SAyDS (2013) published the results of a workshop for the technical exchange to define indicators and variables to assess forest degradation in Yungas. One of the most solid outcomes from the workshop was a list of the potentially best variables for forest degradation assessment. The list included: total basal area, ratio between basal area from species of interest and other species, number of future crop trees, and density of regeneration. Also, a set of thresholds were proposed to recommend activities of forest conversion, enrichment planting, or selective logging. Those thresholds were supposed to be assessed and the results should be published in the short term future, although it was not completed so far.

Brassiolo et al. (2013) and Grulke et al. (2013) proposed for Parque Chaqueño and Yungas, respectively, a set of thresholds based on number of future crop trees and mature trees per hectare, to classify the forest in 4 categories: healthy forest, over mature and useable forest, regenerating forest, and severely degraded forest. This approach defines potential, actual, and future use of the forest, but it would need an intensive forest inventory to map forest degradation, since those attributes are not feasibly sensed with to-date RS techniques. This is even more challenging when the cause of degradation is mixed-severity fires, since the degradation pattern is very diverse (Travis Belote et al. 2015).

Based on the cited literature, a set of variables to measure the indicators of forest degradation (**forest structure** and **growing stocks**) were selected in this research:

Basal area (BA) is one of the most descriptive and used variables to measure growing stocks (Scott & Gove 2002), and has also been used to predict fire-severity (Dunn & Bailey 2016). BA is easy to calculate from trees' diameter at breast height (DBH) measurements in the forest inventory, and that is why it is the basis to estimate statistical error of forest inventories for official use in Argentina (Balducci et al. 2012).

Canopy cover (CC) is a variable especially relevant to measure forest horizontal structure because: (1) it defines the limit between forest degradation and deforestation, (2) it has been used in several studies to assess forest degradation by RS techniques. **Tree height** describes forest vertical structure, and also supports the prediction of growing stocks when it is combined with CC. It is expected that at a constant canopy cover, a forest would have a greater BA when the CC is composed of taller trees. Furthermore, tree heights are also feasibly estimated by RS.

Because this research focuses on the case study of a forest affected by a mixed-severity fire in the Argentinian Yungas, forest degradation is addressed at a stand level, as a result of fire-severity: high classes of fire-severity result in high forest degradation. Fire-severity can be measured based on the proportion of biomass combusted by a fire (Dunn & Bailey 2016). Since a detailed, updated inventory map of forest stocks the year before the fire (2013) is missing, in this research a theoretical benchmark was defined based on the results of an inventory conducted in Florestoona in 2008 (Eliano et al. 2009). The growing stocks estimated in this inventory were considered as the benchmark for 'fully stocked,' from which multiple thresholds were defined as classes of fire-caused forest degradation.

2.2 Remote sensing applied to fire detection and forest inventory

For many years, losses of forest cover have been studied on satellite imagery (Robert et al. 1993, Asner et al. 2002, 2002; Domenikiotis et al. 2003; Souza et al. 2005; Souza & Roberts 2005; Dennis & Colfer 2006; Matricardi et al. 2010). Those studies have been based on reflectance and texture information. Asner et al. (2002) completed a 'band by band' analysis with Landsat ETM+ imagery, focusing on bands 3 (green) , 4 (red), 5 (near infrared [NIR]), and 7 (Short-wave Infrared 2 [SWIR 2]). They compared two systems of logging for the Amazon rainforest 1.5 and 3.5 years after logging. Traditional logging and reduced impact logging were tested in four situations: decks, roads, skids, tree falls. They used an optical plant canopy analyser (LAI-2000) to estimate the canopy and gaps fraction and compared them against the reflectance and texture results. They could verify that the red band was more useful for detecting log-decks immediately after the harvest, because freshly bared soil remained dark, and the NIR and SWIR 2 were more useful to detect the regrowth in the log-decks.

Souza et al. (2005) formulated the Normalised Difference Fraction Index (NDFI) to map multi-temporal damage in canopy from selective logging and forest fire in a transitional forest between savanna and dense forest in Mato Grosso, Brazil. The NDFI combines green vegetation, non-photosynthetic vegetation index, and soil and shade fractions. Previously, Robert et al. (1993) had already defined a set of endmembers to identify non-photosynthetic vegetation index, employing the imagery provided by

Airborne Visible/Infrared Image Spectrometer (AVIRIS) sensors. Souza et al. (2005) applied an algorithm to relate canopy gaps with road, to exclude natural canopy gaps from the ones related to selective logging. For this analysis they used Landsat Thematic Mapper 5 (TM 5) and Landsat ETM+ imagery (30 m/pixel resolution). They concluded that this algorithm is useful to define canopy damage from logging and fire, and were able to find three different classes: intact forest, damaged, and deforested. Souza & Roberts (2005) compared their results from Landsat spot with IKONOS imagery to identify selective logging and forest fires in north-eastern Pará, Brazil. They concluded that IKONOS imagery is useful to detect log landings up to 2 years after logging. The use of these images would reduce the intensity and cost a of ground inventory needed to monitor certified forest areas.

Matricardi et al. (2010) performed regression analysis between canopy coverage obtained by hemispherical photos and several vegetation indices. They accomplished a multi-temporal analysis. Unsupervised classification was used on Landsat TM and ETM+ imagery using IKONOS imagery as ground control. Domenikiotis et al. (2003) studied the potential of NOAA/AVHRR for monitoring and assessment of forest fires and floods. They used the Normalised Difference Vegetation Index (NDVI) to assess and map changes in the vegetation caused by forest fires and floods. The NDVI is an index that indicates the amount of green vegetation, since it uses a ratio between the addition of the reflectance of the NIR and the red channels, and the difference of those same channels' reflectance.

Those approaches using satellite images are sufficient to delineate disturbed areas, but have their limitations with respect to ground resolution, frequent cloud cover, and costs of the imagery. Consequently, Frolking et al. (2009) remarked that those barriers limiting the use of satellite imagery have to be overcome. The use of airborne aerial imagery has addressed these limitations, using stereoscopy to estimate forest structure variables from RS data, but are costly when applied to small areas. However, the development of new aerial digital cameras and UAV produced a renaissance of the use of photogrammetry to assess forest structure (Bohlin et al. 2012).

Recently, several researches have calculated canopy height models (CHMs) from ALS and UAV imagery, and correlated them to forest attributes (Dandois & Ellis 2010; Bohlin et al. 2012; Wallace et al. 2012; Dandois & Ellis 2013; Honkavaara et al. 2013; Lisein et al. 2013; Nurminen et al. 2013; White et al. 2013; Penner et al. 2015; Puliti et al. 2015; Tuominen et al. 2015, Zahawi et al. 2015; Ene et al. 2016; Wallace et al. 2016; Fraser et al. 2017; Puliti et al. 2017; Iizuka et al. 2018; Puliti et al. 2018). However, all those studies need a validation of the data with a ground inventory, since the most accurate information can be achieved with a combination of the two data sources (Gerrand et al. 2011). Area-based inventories combine high-resolution, wall-to-wall, remotely-sensed data with ground information in order to predict forest attributes over the whole area (Næsset 2002; White et al. 2013).

Dandois & Ellis (2010) used the technique *Ecosynth* in the open source software *Bundler* to map and measure tree canopy and aboveground biomass using UAV imagery at the University of Maryland Baltimore County campus. They calculated DTMs and CHMs from ALS and from Ecosynth. From those models, tree heights were estimated and compared with tree heights measured on the ground, finding better results when tree heights were estimated from ALS-CHM than from Ecosynth. Dandois & Ellis (2013) used the Ecosynth technique to predict DTM in three different land covers. DTM was more accurate over forest in leaf-off season than in the leaf-on season, and even more accurate in non-forested areas. Therefore, it is expected that estimations of forest structure variables are more accurate in fragmented areas with small patches of trees than in full-cover forest.

White et al. (2013) did a literature review to compare the potential of using ALS and an image-based point cloud to support area-based inventories by estimating structure attributes. They claimed that ALS has a better explanatory power of canopy density and heights. Lisein et al. (2013) compared the accuracy of two CHMs from an uneven-aged broadleaved forest in Belgium. One of the CHMs was calculated exclusively from ALS, and the other one from ALS-DTM and imagery DSM. The CHMs were very similar, being 96 % correlated, although slightly better definition of crowns were obtained from the ALS-CHM. Dominant height was predicted with an r^2 of 0.82 from the mixed-CHM and 0.86 with the ALS-CHM. Penner et al. (2015) compared the contribution of ALS and image-based point clouds to estimate tree size class distribution in area-based inventories in Canada, where they did not find statistically significant differences between the predictions. These results indicate that tree heights can be estimated fairly well from UAV imagery when a precise DTM is available, as claimed by Nurminen et al. (2013), who also compared ALS and mixed-source CHMs in Finland.

Wallace et al. (2012) used a UAV-borne ALS system combined with HD video and Structure from Motion (SfM) to estimate the position of the aircraft, and assess the spatial accuracy of the point cloud used for forest inventories. Wallace et al. (2016) compared predictions by photogrammetry and ALS-CHM in relatively open Australian forest. They overestimated tree heights with a root mean squared error (RMSE) of 0.92 m from ALS and of 1.3 m from SfM. However, in this study the area was only 1,500 m^2, and the flight altitude only 30 m above ground level, catching 425 images for the area, which would not be applicable in a field-level case study in Argentina, due to the larger extension of the forest lands. Tuominen et al. (2015) conducted an area-based inventory, supported with UAV imagery, in Finland. They combined ALS-DTM with SfM-DSM in order to calculate a CHM. They found similar results in estimation of tree height from SfM and from ALS datasets, when using the same ALS DTM.

Knoth et al. (2013) used UAV to support restoration monitoring in cut-over bogs in Germany. This high-resolution imagery allowed them to use object-based classification not only based on the pixel value, but also on the texture patterns, geometry aspects, segment dimensions and topologies. They had limitations on the positional accuracy, which was between 2 m and 15 m due to the quality of GPS mounted on small

UAVs. They replaced the red band with the NIR because this band is more sensitive to changes in vegetation (Robert et al. 1993). Due to the lack of the red band, the NDVI analysis was not possible.

Bohlin et al. (2012) conducted the area-based approach over a homogeneous forest in Sweden using aerial imagery. They tested different flight altitudes (4800 and 1200 m aboveground level) and overlap (80 % along-track, and 30 % and 60 % across-track). They estimated stem height, stem volume, and basal area with an RMSE of 8.8 %, 13.1 % and 14.9 %, respectively, and found that the tested overlap and flight altitude alternatives did not report significantly different results. Honkavaara et al. (2013) compared photogrammetric DSM before and after a storm in Finland. After trying different overlaps, they recommend 80 % along-track and between 30 and 60 % across-track, and the use of ground control points (GCP) to correct the images.

Ene et al. (2016) compared the precision of estimation of aboveground biomass on a forest inventory supported with wall-to-wall and partial coverage ALS data. The results reported 10 % better precision for the wall-to-wall coverage, but much higher cost of acquisition. They recommended the use of low cost wall-to-wall data, such as satellite imagery, and samples from a more precise source, such as ALS or photogrammetric point clouds. Puliti et al. (2015) estimated BA from a CHM estimated from ALS-DTM and SfM-DSM with a r^2 of only 0.6, but mean height and dominant height with a r^2 of 0.68 and 0.96, respectively. Furthermore, they slightly improved the prediction by including spectral information on the models (r^2 of 0.71 and 0.97 for mean height and dominant height, respectively).

More recently, some researchers tested the combination of ground inventory, a low cost wall-to-wall cover low resolution image, and partial cover high resolution image. For example, Puliti et al. (2017) demonstrated the gains of the 'hybrid inference' approach to improve the precision of volume estimations in forest inventory, combining ground plots with partial cover UAV imagery and full cover ALS data. Fraser et al. (2017) correlated Landsat spectral indices with UAV-derived metrics to assess fire-severity in a boreal forest in Canada. Puliti et al. (2018) combined ground plots with partial cover UAV imagery and Sentinel-2 data on a hierarchical model-based inference to predict ground stock volume. After rigorous statistical analysis, they found similar estimates between this approach (standard error [SE] = 3.53 %) and the area-based approach using ALS data (SE = 3.33 %).

Most of these studies have been conducted over even-aged stands, and counting with a precise DTM. However, Iizuka et al. (2018) addressed the calculation of photogrammetric DTMs on a Japanese cypress forest. Their best estimations were with a cell size of 60 m, maximum angle of 25°, and maximum distance of 1.3 m via adaptive Triangular Irregular Networks (TIN) modelling. However, this resolution is lower than the Shuttle Radar Topography Mission (SRTM)-DTM existing in Argentina (30 m/pixel). Zahawi et al. (2015) used an Ecosynth UAV to evaluate three methods of restoration in an agricultural and cattle grazing production system in southern Costa Rica. They created a DTM based on the 3D point cloud and another with GPS altitudes collected in the field. Deducting this DTM from the DSM, they were able to estimate tree height and canopy openness. They achieved slightly better results with the DTM corrected with GPS data, and recommend it since it should be produced only once. However, depending on the size of the study area and the variation of the terrain, it could be a tedious and time-consuming approach.

In summary, one can conclude that the spatial resolution and cloud coverage of satellite images often limits the assessment of forest resources. Stereoscopic visualisation of images acquired from manned and unmanned aerial vehicles addresses and partially overcomes this limitation, offering a greater flexibility of data acquisition. However, until now, area-based inventories supported with UAV imagery have been conducted mostly over homogeneously structured forests, and were combined with detailed ALS-DTM. A gap of information still exists when it comes to the assessment of open, heterogeneously structured, remote forest lands, wich was addressed in this research. Similar to the approach of Iizuka et al. (2018), in this research the DTM was produced exclusively from UAV imagery. Ene et al. (2016) recommended considering the combination of a low-resolution, wall-to-wall image with a partial cover high resolution image and ground data. Such a procedure would add a third stage on the typical 'two stage' area-based approach of forest inventories. In this research, this recommendation was considered in order to test whether or not the inclusion of partial cover UAV imagery could reduce the classification error of a satellite image used in an area-based inventory.

2.3 Forest management units

Recent remote sensing concepts and technologies have demonstrated to deliver a very detailed delineation of the actual forest structure, even under rough terrain conditions. However, when it comes to planning and implementing rehabilitation measures on the ground, those homogeneous areas can be too small. In those cases, the establishment of forest management units (FMU), aggregating small stands into meaningful management areas, is necessary in order to facilitate forest operation planning and implementation across the whole forest. The concept of FMUs refers typically to two different scales: site (Oregon State University 2017) and regional (Kim et al. 2016). In this research, FMUs are established in Florestoona forest, where the delineation of areas with similar conditions of forest stocks are desirable (Oregon State University 2017).

When a detailed map reporting quantitative characteristics of the stands is available, it is possible to apply spatial statistics in order to test spatial autocorrelation among those variables (Nelson & Boots 2008; Noce et al. 2016). If positive autocorrelation is confirmed, a hotspot analysis should be conducted to identify where the areas with low or high values of the variable of interest are located. There are several hotspot methodologies, some engaged on the difference between a local feature and neighbours (spatially local definitions), and others comparing a single observation with the full dataset (spatially global definitions; Nelson & Boots 2008). From the only few hotspot analyses applied in ecology, the most common are Kernel Estimations and Local Measures of Spatial Autocorrelation (Nelson, Boots 2008), and are applied to local autocorrelation. However, a third autocorrelation method raised from the combination of both scales (local and global) is often applied. The most popular of the third group of methods is the Getis-Ord Gi* statistics, which compares local patterns to a global threshold (Nelson & Boots 2008).

Even though hotspot analysis was originally developed in geography, there are already some researches applying it to ecology. Identifying areas with unusual measures of a variables of interest (hot and coldspots), would help natural resource managers to allocate limited resources (Fei, 2010). For instance, Noce et al. (2016) mapped hotspot of forest species diversity in the Mediterranean basin with the aim of identifying areas with high value of conservation; Feltman et al. (2012) used hotspot analysis to forecast wildfire occurrence in South Carolina; Potter (2009) also detected hotspot of fire occurrence in the USA to identify areas of greater risk of fire occurrence; Vadrevu et al. (2013) used hotspot analysis (k-means analysis) to identify hotspots of fire intensity in India; and Harris et al. (2017) used hotspot analysis to map forest loss. The closest work to this research is the one from Bemman et al. (2015), which shows the results of applying hotspot analysis for the formation of FMUs of small properties of belonging to the railway company Deutsche Bahn across three German federal states for the production of short rotation coppice.

Spatial statistics are run based on a reference distance, which defines the local areas being analysed (Getis & Ord 1992; Noce et al. 2016). The distances used should be based on the objectives of the analysis and knowledge of the environment. For example, spatial statistics with the objective of assessing landscape connectivity (Saura & Pascual-Hortal 2007; Saura & Torné 2009) would select thresholds based on the dispersal distance of certain animal or plant species (Pascual-Hortal & Saura 2006). However, due to lack of information of the environment, in most cases, knowledge-based distances are difficult to determine, and some studies define them arbitrarily (Nelson &

Boots 2008). Noce et al. (2016) proposed to conduct those analyses in a multi-scale scenario, where several distances are considered and the resulting maps are compared.

If a hotspot analysis is applied without regard to the global autocorrelation, statistical error Type I might be abundant (Ord & Getis 2001). Therefore, a more conservative analysis can be applied by the use of False Discovery Rate (FDR). This reduces the number of cases where the null hypothesis was rejected when there was actually a random distribution of features (Benjamini & Hochberg 1995), by eliminating the weakest features for which the null hypothesis was rejected. It is based on the spatial dependency that features near to each other tend to be similar, and the neighbouring features overlap due to the hotspot analysis. Therefore, the greater the distance set for the hotspot analysis, the greater the overlap and spatial dependence.

In this research, the tool 'Hot Spot Analysis (Getis-Ord Gi*)' from the environment ArcGIS 10.3 was used, applying FDR in order to identify clusters of low and high values of a selected variable indicating forest stocks and structure (Adjusted Canopy Cover Index, ACCI) in a multi-scale scenario. The resulting coldspots would be considered as FMU where, due to the lack of stocks, intensive enrichment planting (EP) is necessary, whereas in the resulting hotspots, EP is necessary at a lower scale. Additionally, because EP could require the logging of some native forest patches, spatial statistics are applied to assess landscape connectivity and the effect of EP over those low-stocked areas.

2.4 Enrichment planting

EP is one of the most commonly used practices for the rehabilitation of degraded forest. This method increases the commercial productivity while maintaining the sites as essentially native forest (Lamb & Gilmour 2003). The basis of this practice is to increase the number of trees of the desired species improving the production, while much of the original biodiversity is still present (Lamprecht 1990; Keefe 2008; Balducci et al. 2012; Zulle et al. 2015). EP activities must take place only when the stand is damaged so heavily that natural regeneration (and sustainable forest management) is severely limited (Lamprecht 1990; ITTO 2002). In the case of degradation caused by fire, EP is recommended within the first three years after the fire (US Forest Service 2016). However, when natural regeneration is good enough to assure a future valuable forest, it is a better option to concentrate the management of this regeneration and not to apply EP (Lamprecht 1990). In cases of extremely severe degradation, two phases of EP-operation may be necessary; a first one to ameliorate the site condition, often with light-tolerant, fast growing (often exotic), adapted species, and a second stage with native species under the umbrella of the trees planted in the first stage (Lamb & Gilmour 2003). In temperate climate conditions, the secondary forest surrounding the planted areas must fulfil the protection for frost-sensitive species (Montagnini et al. 1997) as well as for the shade-tolerant species (Ådjers et al. 1994). Furthermore, silvicultural operations should encompass the whole management unit to encourage the establishment of natural regeneration in those secondary forests surrounding the enrichment areas (Montagnini et al. 1997).

Most of the to-date known cases of EP have used a line planting approach. The degraded forest is opened in lines of a constant distance, and seedlings are planted in a single line (Lamprecht 1990). Beside the planting line, tending measures take place in order to reduce competition with secondary vegetation. Lamprecht (1990) proposes, for tropical forests, to extend the tending on 50 % of the management unit with the following arrangement: all vegetation must be removed at 1 m from both sides of the axis of plantation; up to 5 m each side all brushes, young trees up to 4 m high and wide-crown lower-story trees must be removed; a 10 m wide strip must be left with permanent natural forest cover. However, those recommendations were not considered in many cases, and most of the line EP implemented in Latin America in the last 60 years did not achieve the expected results. Most of the practitioners limit the tending to a narrower area beside the planted trees, causing (1) a tunnel effect of the native forest, which limits the sunlight (Lozada et al. 2013), and (2) a high cost of repetitive tending operations, which are not sustainable in time (Noguera et al. 2006).

Noguera et al. (2006) analysed the projected economics of EP in the Venezuelan Guayana within an optimistic scenario that the EP species would reach a diameter at breast height (DBH) of 40 cm, and a commercial stem height of 14 m within 40 years. They intended to plant 100 trees/ha and to harvest 56 of them. However, even in a scenario of ideal growth, the net present value (NPV) is negative due to the high cost of cultural treatment (15 weeding, four liberation thinning and one pre-commercial thinning). Lozada et al. (2013) also tested line EP in the Venezuelan Guayana for five native species. They found longer rotation periods than the same species would have in native forest without intervention, due to the competition of the native forest. Therefore, Rodriguez et al. (2011) tested the positive border effect by forest roads, and recommended avoiding traditional single line planting, and to construct wider roads (20 m) along which double line EP should be implemented.

Ådjers et al. (1994), found that line orientation has little influence on the survival rate of the *Shorea sp.*, southeast-northwest being the peferred one. Based on their results, line width did not affect the survival, but it did have effect on growth in the first 2 years after the plantation, because the trees took advantage of light in wider lines.

Other researchers were more optimistic about line EP, but still saw limitations due to tending frequency and the related cost. For example, Montagnini et al. (1997) did a cost/benefit analysis in a line EP, and found positive results on the region 'Selva Paranaense,' Argentina. Lines were 2 m wide, but expanded to 4 and 6 meters on the second and third years after plantation. During those 3 first years, weeding occurred 3 times per year. EP lines were 150 m long and separated by 8 m between the longitudinal axes. Even though the financial rate of return was claimed to be lower than other alternatives in the region (no specific data was given), they assure that it would be a lower risk investment. Montagnini et al. (2006) tested several natives species in Misiones, Argentina in group EP of 18 m x 18 m. Trees were planted on a planting distance of 3 m x 3 m. They also tested an agroforestry system, where fruits or *Ilex paraguariensis* A. St.-Hil (Aquifoliaceae) are associated with timber species. Trees were planted every 6 m on group EP of 15 m x 15 m. They recognised a high cost of tending, especially in the first years of plantation, and a high susceptibility to plague attacks, since the planted trees would be more exposed due to weeding.

Small group (or gap) EP, and sowing were tested, but with limited success due to competition with the native forest. Senilliani et al. (2006) measured DBH growth of the species in small group EP in post-harvesting gaps (average 2 trees/gap) in the province of Chaco. They found maximum DBH growth of 1.3 cm/y on 'Ibira Pitá' (*Peltophorum dubium* Spreng, Fabaceae) at the age of 16 years. They recommended thinning the surrounding native forest at the age of 10 and 13 years, because the high competition caused mortality and low growth rates on the planted trees. Schulze (2008) studied the financial and technical aspects of EP in logging gaps (sites between 165 and 455 m^2) in eastern Amazon, and found an economical advantage in this practice compared to the traditional line EP. Schwartz et al. (2017) measured timber production on 13 year old gap EP on a degraded forest in the Brazilian Amazon. They found that the financial benefits are highly linked to the future price of the forest products. Comparing with a control area (native forest without EP), the economic benefits were found only when EP increased the production of high grade saws and veneer logs, but not when they produced more round wood of medium to low quality. Ramos & del Amo (1992) tested the response of group-planted seedlings, and of seeds exposed to a different light transmission through the canopy in a secondary forest in Veracruz, Mexico. The highest opening they tested (68 %) showed the best results of height growth in the first years, which is regarded as a key factor for EP to succeed (Dawkins 1958), although after 80 months the survival rate was best in the situation of mild light transmission (37 %). However, those results may depend directly on the shade tolerance regime of the planted species. Also, in this case, the authors stated the high cost of tending as one of the hurdles for the success of EP.

Sowing was also tested by Seltzer et al (2015) in order to improve the economy of EP. Since seeds may be easier to transport, store, and plant, and may be less expensive than using seedlings, they established experiments of sowing in a NTFP extraction system. However, only 10 % of the planted seeds survived rodent attacks, and only 2.2 % of the plants survived 11 months after planting. This practice is even less viable when the understory vegetation (grass, lianas, shrubs) are abundant, as is the case in Yungas (Arturi et al. 2006).

When establishing an EP project in a degraded Yungas forest in Argentina, the percentage of planted and weeded areas, as well as the EP design, is still under discussion. Due to the low yield of line EP so far, Brassiolo et al. (2013) suggested that other designs should be tested e.g. strips and big groups. Those designs would reduce the competition between the planted trees and the secondary forest (Di Marco, 2014). Noguera et al. (2006) recommended studying new planting designs, and made reference to the study of Vicent (2004), who proposed EP in areas between 1 and 5 ha on the tropical forest of the Venezuelan Guyana, following the nomadic agriculture system.

Some studies have been conducted on strips EP, and, as expected, some authors found that the wider the strips of EP, the better the growth of the planted trees. Vidaurre et al. (2000) studied the effect of light on the growth of the species *Cedrelinga catenaeformis* Ducke (Fabaceae) on the Peruvian Amazon. They found significantly better growth of the species in conventional plantations (not-under-cover) and in the widest strips of EP they tried (30 m). Flores Bendezú et al. (2004) reported one of the most positive experiments. They tested native species response 20 years after EP in Peru with a plantation spacing of 3 m x 3 m in openings of 30 x 33 m. They found that *C. catenaeformis* is the tested species with the greatest growth in EP. They found survival rates between 28 % and 79 %, and mean annual increment (MAI) of DBH ranging from 0.63 and 1.96 cm/y. Two thirds of the trees showed a desirable shape (straight and rounded trunks). Other tested designs were strips of 5, 10, and 30 m wide, and planting distance ranging from 2.5 to 15 m. The survival rate ranged from 46 % to 73 %. DBH-MAI, ranged between 1.58 and 0.98. For the same species, better results were found in big groups than in strips.

Additional to size and planting designs, a selection of species adapted to site and situation is one of the most important factors for successful EP to thrive. Del Castillo et al. (2011) reported the response of 'toona' (*Toona ciliata* M. Roem., Meliaceae) and 'tipa colorada' (*Pterogyne nitens* Tul., Fabaceae) in an experimental plantation in Yuto (Salta, Argentina) at the age of 10 years. In order to conduct line EP, native forest was eliminated in strips of 4 m wide, and seedlings were planted every 5 m. They reported that 'toona' grows 3.04 cm/y in DBH and 'tipa colorada' only 1 cm/y. Montagnini et al. (1997) cited Gartland (1974), who found that 'paraíso' (*Melia azedarach* L.; Meliaceae) can, in 2 years, overtake the 4 m hight of the secondary vegetation, showing the potential of the species for this practise, since one of the most important characteristics is rapid vertical growth (ITTO 2002). 'Paraíso' and 'toona' are the one of the main species used on the EP conducted in Florestoona.

In the Argentinian Yungas, EP is prescribed on the guidelines for sustainable forest management (Grulke et al. 2013) in cases where there exists either an over-mature forest with insufficient future crop trees (less than 100 trees per hectare), or if the forest is degraded so heavily that there are not enough mature trees nor future crop trees for a selective management system. However, the size of the enriched areas plays an important role, since, when the enrichment is practiced over a high percentage of the area, the result would tend to become a monospecific forest (Brassiolo et al. 2013). SAyDS & MAGyP (2012) recommend transforming up to 30 % of the forest area, opening lines up to a width of 3 m, since, under the criteria of SAyDS and MAGyP, the enrichment planting in groups would be considered a small conventional plantation. In contrast, Balducci et al. (2012) and Brassiolo et al. (2013) recommend opening lines up to a width of 4 m, strips up to a width of 18 m, and they also considered EP in big groups, opening areas up to 2,500 m^2, since under this system the planted trees face less competition with the native forest.

The reported experiences of EP conducted in Argentina, and other South American countries, revealed shortcomings in their implementation. In most of the cases, the recommendations suggested by Lamprecht (1990) for line EP were not followed, and tending operations were limited to a small area close to the plants. Furthermore, the recurrent weeding operations required by line EP raises the cost in the first years, negatively affecting the financial aspect of this long term activity. As there are only a few EP experiments existing in Yungas forests until now, trials on a larger scale, and broader discussion, are necessary. It seems logical, as proposed by Vicent (2004), to think in bigger areas of EP in order to mechanise tending operations at lower cost. Additionally, the planted species should first provide revenues to the forest owners, who face a reduction of income due to the degradation of their resources. Adaptive EP approaches (designs, density, species, and size) should be tested and implemented.

3 Regulatory framework

When defining attributes and thresholds for the analysis, planning, and preparation of interventions in degraded forests, all legal or regulatory requirements have to be taken into account. Therefore, a brief overview of the relevant certification schemes and legal prescriptions are given in this section. Since the case study field is located in the province of Salta, Argentina, a subsection is dedicated exclusively to the regulations in this province.

3.1 Forest certification schemes in Argentina

Forest certification is granted through the certification bodies which assess management and production against criteria and indicators. There are also numerous environmentally engaged organisations attempting to assess sustainable forest management (SFM), e.g. (ITTO 2002) has developed standards to describe criteria and indicators which can be used to define SFM, but without fixing thresholds for assessment (Higman 2005). However, forest certification bodies have developed indicators and related measurement/assessment procedures and thresholds addressing ecologic, economic and social criteria (Higman 2005; Cubbage et al. 2010). In many cases, certification systems aim at defining specific thresholds applicable for the respective country or region where they operate, in additional to having an international standard. Forest Stewardship Council (FSC) is often considered one of the prime examples of certification systems, since its standards are regarded as the most reliable and ambitious (Fundación Vida Silvestre 2014). On the other hand, The Programme for the Endorsement of Forest Certification (PEFC) is the largest certification system, with more than 300 million hectares certified worldwide (PEFC 2018), but with a standard regarded as more flexible.

For further information about how certification mechanisms work, it is recommended to consult Higman (2005).

3.1.1 *Overview of the main certification schemes relevant to Argentina*

3.1.1.1 FSC

FSC is a non-profit, non-governmental, membership-based organisation, founded in the USA in 1990, with the aim of identifying forest products that come from sustainably managed forests (Pietras 2012). FSC operates with a set of 10 principles and criteria (P&C) that apply to all tropical, temperate, and boreal forest. Many members apply for plantations and partially replanted (enriched) forests (FSC-STD-01-001 [version 4.0]). Those principles are mainly designed for the management of forest for timber production, but are also applicable for forest management oriented at the production of non-timber forest products (NTFP). Based on the P&C in the FSC system, national or regional FSC official certification bodies are installed and supposed to develop a set of standards adapted to their region, against which assessment takes place.

- Principle 1: Compliance with laws and FSC Principles
- Principle 2: Tenure and usage rights and responsibilities
- Principle 3: Indigenous peoples' rights
- Principle 4: Community relations and workers’ rights
- Principle 5: Benefits from the forest
- Principle 6: Environmental impact
- Principle 7: Management plan
- Principle 8: Monitoring and assessment
- Principle 9: Maintenance of high conservation value forests
- Principle 10: Plantations

FSC offers 3 different types of certification based on the origin, the stages, and the progress of the forest products through the value chain.

- Forest Management Certification: confirms that a forest area is managed under the FSC's P&C. The certification bodies send experts to the field to assess that the forest management follows economic, social and ecological sustainability.
- Chain of Custody Certification: allows companies to label FSC products, enabling the consumers to identify and buy certified products and thus promote sustainable forest management.
- Controlled Wood: certifies that forest products do not come from unacceptable sources, and therefore can be mixed with FSC certified products and labelled as FSC Mixed products. Unacceptable sources are:
    - illegally harvested wood,
    - wood harvested in violation of traditional and human rights,
    - wood harvested in forests in which high conservation values (HCV) are threatened by management activities (HCVs are areas particularly worthy of protection),
    - wood harvested in forests being afterwards converted to plantations or non-forest use, and
    - wood from forests in which genetically modified trees are planted.

FSC was promoted in Argentina from 2002 to 2006 by Fundación Vida Silvestre (World Wide Fund for Nature [WWF], Argentina). In 2006, a new committee (Consejo de Manejo Responsable de los Bosques y Espacios Forestales) was founded by several national relevant organisations to be in charge of standardisation and FSC certification in Argentina, but without success. At the moment, all the certifications in Argentina are therefore carried out according to the generic FSC International, because there is no FSC body engaged in the project at national level.

Only the 'FSC Controlled Wood Risk Assessment' (FSC-STD-40-005 V-2.1) was developed for plantations, and scopes exclusively for the provinces of Misiones, Corrientes, Santa Fe, Entre Rios and Buenos Aires. There are other types of FSC certification in Argentina, such as Forest Management, and Chain of Custody, but they are based on the FSC generic International Standardisation, until specific standards are developed for the country. On July 2018 there were 469,122 ha in Argentina certified under FSC-Forest Management, 118 companies under Chain of Custody, and only one has Controlled Wood standards (FSC 2018).

3.1.1.2 Program for the Endorsement of Forest Certification (PEFC)

PEFC is the biggest certification body, worldwide. This organisation endorses national certification systems which have to develop standards in line with the PEFC requirements. The PEFC approves national certification systems after evaluation based on the following criteria:

- The PEFC Council Standards, setting out the requirements for regional, national or sub-national systems, are transparent and widely communicated.
- The endorsement and mutual recognition of forest certification systems and standards relies on their independent assessment.
- The assessment process is transparent and consultative.
- Assessment results, and the assessment reports, are made publicly available by the PEFC Council.

Adopting all PEFC principles and criteria, in August 2014 the Argentine Forest Certification System (CerFoAr) was endorsed by the international PEFC, giving the forest managers an option to certify their production with this international label (Ambiente Forestal NOA 2017). CerFoAr is an IRAM (Argentine Institute for Normalisation and standardisation) standard which establishes criteria, principles and indicators for sustainable forest management in Argentina. The Asociación Civil para la Administración del CerFoAr is in charge of developing rules for the implementation of CerFoAr in Argentina. IRAM is the Argentinian organisation for the International Organisation for Standardisation (ISO), Pan-American Commission for Technical Norms (COPANT), and the Mercosur Association for Normalization (AMN).

The CerFoAr works based on the following IRAM norms:

- IRAM 39800: Sustainable forest management: setting vocabulary, terminology and definitions.
- IRAM 39801: Sustainable forest management: setting principles, criteria and indicators for the management unit.

  This norm has 7 principles, and more criteria for each principle.

  - Principle 1: Compliance with the law
  - Principle 2: Search for forest resources sustainability
  - Principle 3: Maintenance of forest resources vitality, health and productivity
  - Principle 4: Biological diversity maintenance
  - Principle 5: Water, soil, and air care
  - Principle 6: Economic and social growth of the local community in which the forest activity exists
  - Principle 7: Monitoring and control
- IRAM 39802: Sustainable forest management: ruling the chain of custody. This norm is based on the PEFC document (Annex 4): 'Chain of Custody Based Products, Requirements.'
- IRAM 39803: Sustainable forest management: setting rules for audits.
- IRAM 39804: Sustainable forest management: setting additional guideline for audit process. This norm is still in process.
- IRAM 39805: Sustainable forest management: setting rules or group certification.

3.1.1.3 Comparison of the two certification systems for rehabilitation of degraded forests

The greatest difference between sustainable forest management certification by PEFC and FSC in Argentina is that PEFC has developed and implemented specific criteria for the country, whereas so far FSC did not. In general, both standardisation schemes aim at compliance with the economic, social and environmental criteria. As no specific FSC standards are developed in Argentina, it seems logical to take for the comparison standards approved in neighbouring countries, such as Chile.

Regarding land use change, FSC's principle 6 clarifies that the conversion of native forests to other type of forest or non-forest land uses are allowed only when it affects a small portion of the management unit, and does not affect HCV forest. Furthermore, this new management should enable long term conservation benefits. In principle 4-1 from IRAM 39801, it is requested that biodiversity must be assured by not reducing HCV native forest surface by other means. Criteria 2-3 from IRAM 39801 specifies that a forest inventory must be developed to assess the forest conditions, and in the case that forest dynamics are unclear, precautionary mesures must be applied to assure forest sustainability long-term. This is also required by FSC in their principle 7-1.

FSC's principle 6-3, 'ecological functions and values shall be maintained intact, enhanced, or restored,' assures the future stability of the forest for restoration/rehabilitation to. In the USA, enrichment planting is one of the measures approved by the FSC, when forest managers plan to restore degraded areas (FSC-US 2011). However, for large scale areas in Chile, rehabilitation of degraded forest with exotic species is approved up to a rate of 20% of the total enriched area (Criteria 6-9-2 of Standard STD-BN 201205- 311209). IRAM 39801, in principle 2-4, specifies that natural regeneration must be evaluated and, if necessary, specific measures should be adopted, although this must be implemented with ecological criteria, since natural forest connectivity must be assured, based on principle 4-1.

FSC Principle 10 is valid for plantations and partially replanted forests, which also includes enrichment planting. FSC does not allow the conversion of natural forest areas to plantation, but they allow those plantations which promote forest restoration, protection, and do not increase pressures on natural forest. The management objectives of the restoration shall be explicitly stated in the management plan, and clearly demonstrated in the implementation of the plan. The selection of the species should be appropriate for the management objectives, and native species should be preferred over exotic species. Exotic species are eligible when their performance is proved to be greater than native species, although ecological impacts should be monitored. No species can be planted at large scale before trial plantation have shown that they are ecologically well-adapted, and are not invasive. IRAM 39801 does not have specific rules for plantations, since all their principles apply to natural forests and plantation.

3.2 Legal framework

3.2.1 Argentina

Argentina counts 27.4 M ha of native forest and 1.2 M ha of forest plantations (ASORA 2017), but the national market of forest products is still in deficit, and represents negative 700,000 USD to the country (Vaca 2017). The distribution of forest areas in Argentina is concentrated in the three provinces (Misiones, Corrientes, Entre Ríos) located in the northeast of the country, producing 88 % of the gross domestic product (GDP) related to the forest sector (MAGyP 2015). 8 % is produced in the centre of the country, and the remaining 4 % in other areas. In order to strengthen the Argentinian forest sector, policies are necessary to increase its productivity and competitiveness (ASORA 2017).

Argentinean forests were spread across 100 M ha in the year 1900, which was 35 % of the total land surface. More than 70 % of the forest cover was lost in a century, most of it through a systematic conversion process to agricultural lands. In the period between 1990 and 2000, Argentina faced one of the highest deforestation rates in the world (-0.8 % annually). More than 45 % of the deforestation in the country was due to the conversion to grassland for cattle production, and 43 % to agriculture for commercial crops (FAO 2016). Furthermore, unstable national economic policies and legal insecurity may make investors avoid long-term land use projects on forestry in the country (Diario EPOCA 2015). Consequently, today's forest policies in Argentina are focused on the promotion of forest production and the protection of the remaining natural areas, which are in part threatened by the extreme competition for land use for agriculture. For instance, the national forest law 26331 (2007) has the primary objective to promote conservation through forest land planning and the regulation of the expansion of agriculture and other land uses.

Listed here are the most relevant national laws for forestry issues, and related decrees:

- Law 13273, released in 1948 for the defence of the forest patrimony. A national commission was created to be in charge of monitoring the compliance with this law.
- National decree 710/95, released in 1995. The provinces were obligated to create their own organisation to monitor forest activities in their respective territory.
- Law 24857, released in 1997. This law offers tax stability for 30 years to all those forest management projects which have an approved management plan.
- Law 25080, released in 1998, for the promotion of forest plantations, by granting financial support to plantations aiming to produce timber.
- National law 25675 (General Law for the Environment), released in 2002. The national government established recommendations for the adequate application of minimum levels of protection, and the provinces had to adapt their own laws to those levels.
- Law 26331, released in 2007, for the promotion of the sustainable management of native forests, established schemes of financial support to forest owners.

The two most relevant laws for the management of degraded forests (law 25080 and law 26331) are shortly described:

3.2.1.1 Law 25080

National law 25080 (1998, regulatory decree 133/99) and its prorogation (law 26432, 2008) supports the first-time establishment of plantations and enrichment planting (EP) of certain species in native forests by financial subsidies, with the maximum amount of 80 % of the total costs of implementation. EP is defined by the regulatory decree 91/2009 (related to law 26331) as '*the restoration activity in a native forest, aimed to increase the number of plants, species or genotypes by planting or seeding native forest species* *in between the pre-existing vegetation.'* However, law 25080 promotes the plantation of mainly exotic species. According to the regulatory decree 133/99, EP should be completed by assuring the increase of forest production per area unit, and taking care of biodiversity.

Subsidies offered by this law are different according to the province, species, plantation density, and implementation system, e.g. if irrigation was used or not. For those forest owners who plant less than 300 ha/y, subsidies cover 80 % of the estimated costs; between 301 and 500 ha/y, the subsidies cover only 20 % of the estimated plantation costs. Above 500 ha/y, no direct subsidies are offered, but rather tax benefits. For enrichment planting, a special financial support scheme has been established. The expected costs are covered by 80 %, independently from the number of involved hectares. All subsidies are granted against proving the effectiveness of the plantation 18 months after plantation. Thinning and pruning are also financially supported.

Table 1 shows the species, plantation density, and payment granted for the plantations achieved in the year 2016 in the provinces of Salta and Jujuy. Those values are based on national resolution 219-E2016.

Table 1: Cost estimation for plantation of the subsidised species in the province of Salta during 2016, based on resolution 219-E2016. A maximum of 80 % of those costs are subsidised according with the total plantation area. The conversion to Euros was calculated at a rate of 1 EUR = 16.2 ARS, which is the average for 2016.

Species	**Density Plants/ha**	**Estimated costs in ARS (and EUR) per ha**
Pinus sp	From 600 to 699	22,920 (1,415)
	From 700 to 949	24,237 (1,496)
	950 or more	26,228 (1,619)
Eucalyptus sp	From 600 to 699	14,923 (921)
	From 700 to 949	16,483 (1,017)
	950 or more	18,824 (1,162)
Prosopis sp	From 400 to 499	18,390 (1,135)
	From 500 to 700	24,895 (1,537)
Toona sp	From 400 to 499	19,160 (1,183)
	500 or more	24,206 (1,494)

There is a special payment for EP in Yungas, with an estimated cost of plantation of 23,461 ARS (1,448 EUR) per ha, meaning a fixed subsidy of 18,769 ARG (1,159 EUR) per hectare. This is established under the understanding that in cloud forest formation, a special cost of plantation is incurred.

3.2.1.2 Law 26331:

National law 26331 (Minimum Levels of Environmental Protection for Native Forest, 2007- Regulatory decree N° 91/2009) restricts the overuse of forests. Native forests are defined under this law as '*natural forest ecosystems composed mainly of mature native tree species associated with diverse flora and fauna species in their surrounding environment (soil, subsoil, atmosphere, climate, water sources), determining an interdependent net with own unique characteristics and multiple functions which, in their natural condition, give a dynamic equilibrium to the system and offer diverse environmental services to the society, besides all the natural resources with economical use potential.*' This laws requires the province governments to develop a land use planning map classifying their forests into three levels of conservation significance: (1) high protection value, which should be coloured red in the maps; (2) forest land for which forest coverage should be kept, coloured yellow; and (3) areas with high production potential (suitable for land use conversion), coloured green. Those categories are related to different restrictions, which should also be defined by province governments, but always above the minimum protection levels dictated by the national government. Even though there are no numerical threshold for those established restrictions, the classification must take into consideration:

- Minimum habitat area
- Connectivity with other natural communities
- Existence of other biologically outstanding values
- Connectivity between ecoregions
- Conservation status
- Forest potential
- Sustainable potential for agriculture production
- Watershed conservation potential
- Native communities and small farmer settlements' values

Management and rehabilitation activities receive financial support against the application of an approved sustainable management plan by the Provincial Environmental Ministry. A detailed description of activities to be completed the first year of the plan must be added to the overall project. Once approved, the activities related to the ongoing year would be subject to financial support by the state. Even if financial support is not claimed, a management plan must be presented, because any intervention is forbidden until the plan is approved. A forest can be reassigned to another category if proven that it was not properly assigned. Requests for these kinds of modifications are open every five years, and can be required by any interested stakeholders (land owner, NGOs, GOs).

Under this law, EP is a technique which may be used for forest rehabilitation aiming to increase the number of trees, species or genotype in a native forest by planting or sowing native forest species in between the pre-existing vegetation. Exotic, non-invasive species can be used for EP in the first stage, aiming to stimulate a succession process, but this is only allowed in the case that the exotic species are suitable for the existing level of degradation, and only until the environmental conditions are proved suitable for native species.

3.2.2 Province of Salta

The province of Salta has adhered to the most relevant national forest laws by use of provincial laws, as follows:

- Law 13273, in Defence of the forest Patrimony, by the provincial law 5240 (1978)
- Law 25080, by provincial law 7025 (1999), decree 690/1999 and regulatory decree 3990/1999
- Law 26331, for the Minimum Levels of Environmental Protection for Native Forest, by provincial law 7543 (2009), decree 5770/2008, and provincial decrees 2785/2009, 3676/2009, and 2211/2010

Provincial decree 15142/1960 established the minimum log diameter for harvesting valuable timber species (See annex 1). Those values have not been changed since this decree was released in 1960, even though the stocks and forest products have significantly changed since then. For the implementation of a sustainable management plan, it has to be approved a-priori by the province government, and must include an evaluation of environmental impact.

To fulfil the requirements of the law 7543 for forest land use planning and the creation of minimum levels of environmental protection, the provincial ministry of environment and sustainable development created the map shown in Figure 1.

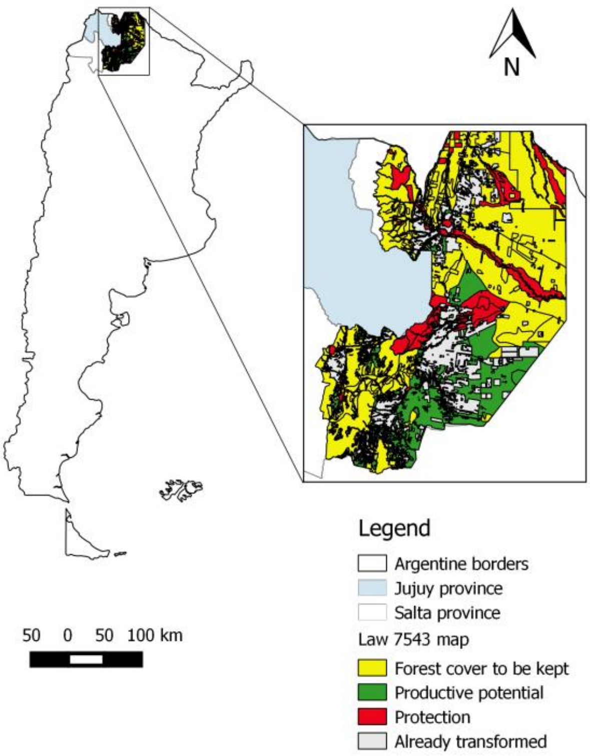


Figure 1: Province of Salta: Forest Land Classification Map according to the law N° 7543 (Status of the year 2009). Scale related to the zoomed area. The northwest of the province is coloured white, since it belongs to the Puna and Mountain Grassland ecosystem, which is arid without forest cover.

For the medium level of protection category (mapped in yellow), there is a great diversity among the provinces defining threshold of inclusion in this category. In this text, we refer only to this category, since it represents the biggest potential for forest activities, including EP. In Salta, 5.39 M hectares are classified in this category, representing 52.7 % of the forest land in the province. The detailed prescriptions (law N° 7543) are as follows:

(1) In forest areas under 15 % slope of terrain, due to the conservation of their biodiversity potential, environmental services, forest potential, or for being a local tribe's habitat, their forest coverage must be kept. These forest areas should be sustainably managed for timber or NTFP production. Because these forests are frequently located close to areas already converted to agriculture, many of them are overused, especially where the road network is developed, allowing the illegal extraction of forest products. These degraded forests are possibly subject to forest restoration and rehabilitation. For 50 % of the area, forest cover must be maintained. Up to 10 % can be converted to agriculture and pasture production, and for 40 % of the area, land use change is allowed when its goals imply forest use. Protective forest strips are to be kept for fauna and erosion functions.

(2) In forest areas above 15 % slope of terrain that are currently not transformed to other production systems, but that keep forest cover, the forest can be managed for selective cutting, tourism, research, and silvopastoral systems (keeping all forest cover).

(3) In forest areas above 25 % slope of terrain, intervention may be carried out, but according to forest certification standards (e.g. FSC).

4 Materials and methods

4.1 Study area

The study area (Florestoona) is a partially degraded native forest in the temperate piedmont of the Yungas Cloud Forest (Selva Pedemontana de Yungas), 29 km to the northwest from the city of Embarcación in the province of Salta, Argentina (Figure 2). Yungas Cloud Forest is a seasonal subtropical forest located in Argentinian north-western Andean mountains between 400 to 3000 m a.s.l. (Cabreara 1976). Northern Argentina represents the most southern part of this ecological district, which occupies the major area in Peru and Bolivia. In Argentina, it is latitudinally extended over 700 km from the provinces of Catamarca (29° S) through Tucumán, Jujuy, and Salta, to the border with Bolivia (22° S), but the maximum longitudinal extension, is not greater than 50 km (Brown et all, 2001).

Figure 2: Location of the case study field.

4.1.1 *Climate*

The climate is subtropical, with a dry season in winter and spring (Blundo et al. 2016). The annual precipitation ranges from 600 to 1000 mm, being concentrated in the warm months (November to March). During dry season, the maximum precipitation could be lower than 10 mm per month. Annual potential evapotranspiration varies from 997 to 1,140 mm, resulting in a small annual positive water balance (Eliano et al. 2009). Thermal regime is continental, so the climate is warm and humid. Maximum temperatures reach 44 °C and minimum, -2.2 °C. The northern piedmont of Yungas can have years free from frost (Brown et al. 2001).

4.1.2 *Soil*

Yungas are located in an orographic system known as Sub-Andean Hills and Pampa Hills, which were formed during the Andes elevation, and expands in a north-south direction. The landscape has a big fluvial influence, with permanent rivers which start in the montane forest.

The soil type belongs to the Association San Antonio Madrejones 2 (Sat-M2), based on the soil classification for the North-western Argentinian by Nadir and Chafatinos (1990). Those soils are moderately developed. Their texture is fine on the surface, and their particle-size increases with depth. They are poorly drained, with neutral pH, and with a high content of organic matter. Those conditions make this soil type suitable for forest growth.

4.1.3 *Vegetation*

Yungas are one of the most diverse ecosystems in Argentina, where 170 tree species are present, from which 79 % have been adapted to the seasonality by losing their foliage during dry season. Among this great diversity, the most represented families are Leguminosae, Myrtacea, Euphorbicae and Anacardiceae. The floristic composition varies from north to south, presenting three latitudinal groups: north, centre, and south. Furthermore, a great variation of species composition is presented through an altitudinal gradient. Three vegetation types are found in three different altitudinal zones: 'Pedemonte' (400-700 m a.s.l.), 'Selva Montana' (700-1500 m a.s.l.), and 'Bosque Montano' (1500-3000 m a.s.l.).

The case study is located in the northern Pedemonte, also known as the floristic district of 'palo blanco y palo amarillo' (*Calycophyllum multiflorum* Griseb., Rubiaceae; and *Phyllostilon rhamnoides* Taub. Rhamnaceae), due to the frequency and dominancy of these species. Beside those species, 'lapacho rosado' (*Tabebuia avellanedae* Standl., Bignonaceae), 'cebil' (*Anadenanthera macrocarpa* Brenan, Leguminosae), 'quina' (*Myroxylon peuiferum* L. F., Leguminosae), 'afata' and 'lansa blanca' (*Cordia trichotoma* Arráb. and *Patagonula Americana* L., Boraginaceae), and 'urundel' (*Astronium urundeuva* M. Allemão., Anacardiaceae) are also frequent. In addition, other biologic types like shrubs, epiphytes and lianas are present in a great number (Cabrera 1971). Woody lianas are present in the Yungas piedmont forest, and their abundance is decreasing with the altitude. Annual creepers and climbers are also present, increasing in abundance in more severely degraded forests (Brown et al. 2001; Arturi et al. 2006).

Even when the floristic composition of the Yungas has been well studied, the results of the few existing studies on forest growth are not consistent. Nevertheless, individual growth was assessed for *Cedrela lilloi* Sessé & Moc. (Meliaceae) and *Juglans australis* Griseb. (Juglandaceae), reporting maximum annual ring growth of 2 cm and 0.55 cm, respectively (Gasparri et al. 2003; Gasparri & Goya 2006). More forest growth results are expected as, in 2002, a set of 50 permanent inventory plots were established to monitor species turnover, and other forest dynamics, by the University of Jujuy and the NGO ProYungas (Malizia et al. 2012).

4.1.4 Field history of use

Florestoona is a privately owned forest estate of 14,622 ha, from which 2,301 ha are in sale negotiations. In 1987, with the beginning of the construction of the railway line from Tucumán to northern Argentina, the economic development of the forest area started. This not only meant the use of the forest area for the construction of the rail network, but also the new possibility to extract and transport forest products to the consuming centres (Eliano et al. 2009). Since then, high-grade exploitation has been implemented, contributing to the decrease of the economic value of the forest. Furthermore, recurrent fires (in 2003, 2008, and 2013) have affected the forest negatively.

In line with better knowledge about Yungas forest ecosystems and their management, especially in larger forest holdings, more sustainable forest systems have been implemented. Finally, following the national law 26331, Florestoona got approval for its Sustainable Forest Management (SFM) Plan in 2008 for almost 10,000 ha of the total area. The western part of the area above the isoline of 800 m a.s.l. (at the centre and north), and above 700 m a.s.l. (at the south) was defined and left as natural reserve. A part of the forest was assigned to intensive forest management, where, since 2004, different EP trials took place (Figure 3). To meet the requirements of the SFM plan, in 2008 the forest managers collected data by the implementation of a plot-based field inventory of 168 plots (1000 m² each) systematically distributed in the 9,098 ha area of interest (for details, see 4.1.5).

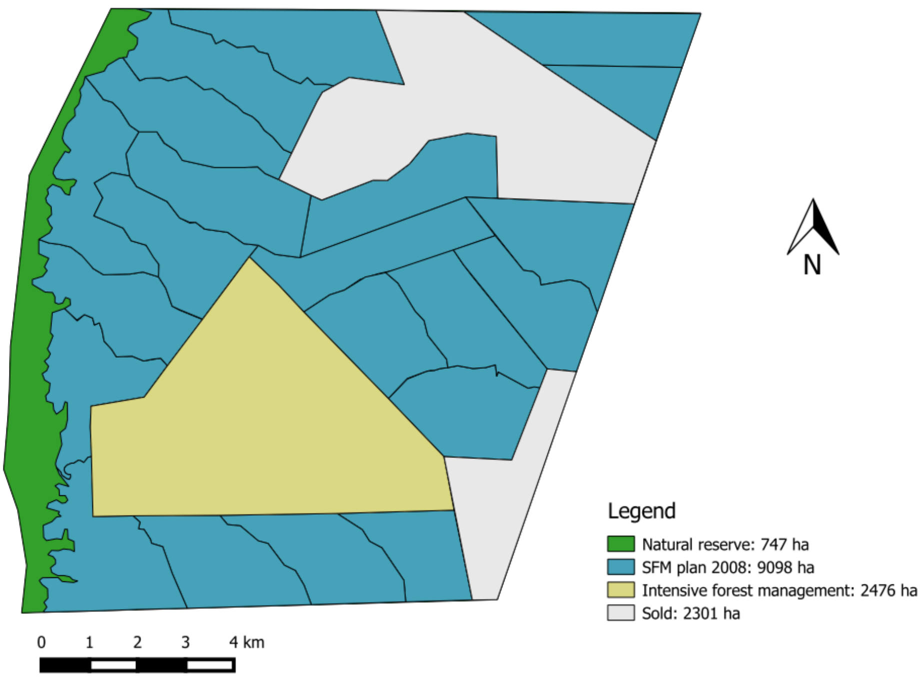


Figure 3: Map of the SFM plan for Florestoona approved in 2008.

Due to the objectives of this dissertation, the forest area defined as the natural reserve, and the plots in negotiations to be sold, are ignored. After an exceptionally extreme dry season, a wildfire took place in November 2013, mainly in the central and southern part of Florestoona, affecting mainly the area under intensive forest management. The fire perimeter was extracted from a Landsat 8 scene from December 19th 2013. The burned area occupies 3,944 ha, out of which 2,021 ha belongs to the area dedicated to intense forest management, and 1,921 ha are delineated for the SFM plan area (Figure 4). The research of this dissertation is focused on those 3,944 ha affected by the 2013 wildfire.

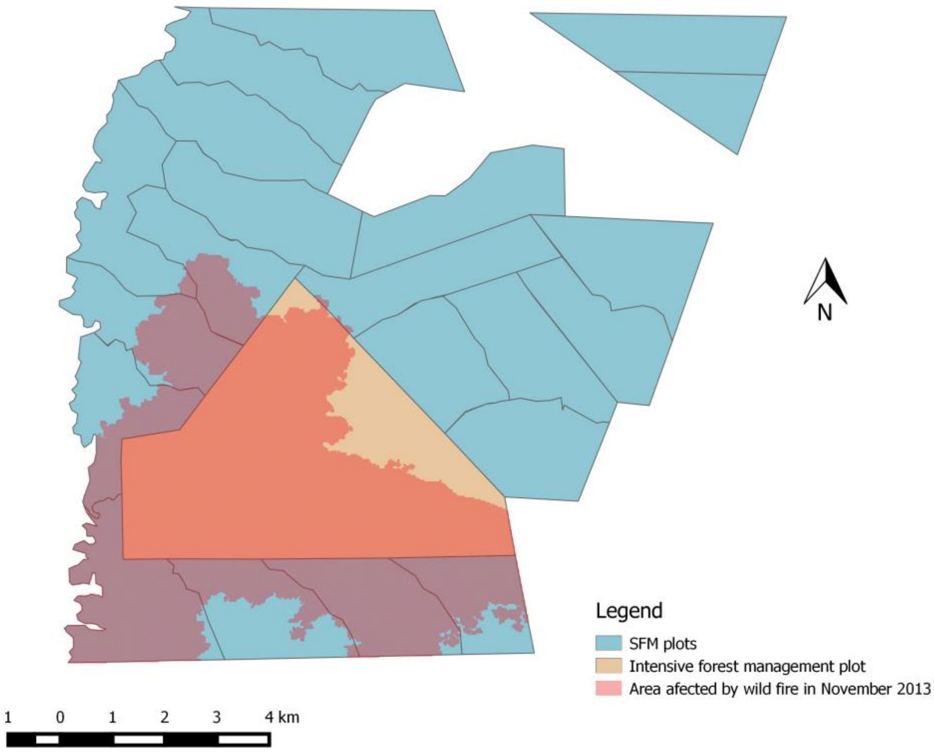


Figure 4: Affected area by wildfire in November 2013. Delineation based on a Landsat 8 scene from December 19th, 2013.

4.1.5 Inventory 2008

In order to set a homogeneous benchmark along the forest, the results of the inventory conducted in Florestoona in 2008 (Eliano et al. 2009) were considered. Those authors made a protocol to write an SFM plan, and conducted a case study in Florestoona. The area of interest is limited by an altitude isoline of 700 m a.s.l., which is considered to be the upper limit of the phytogeographical area of Selva Pedemontana de Yungas (Brown et al. 2001).

The data of the plot-based forest inventory collected by Eliano et al. (2009) is considered the benchmark of a healthy (not degraded) forest status. The following attributes are highlighted:

- Tree abundance (greater DBH than 10 cm): 260 trees/ha
- Basal area: 17.15 m^2/ha, typical of an open forest in Yungas Pedemontana.
- Average Basal area of 8 most wanted species: 10.32 m^2/ha
- Tree health is good for 70 % of the trees, 10 to 15 % of the trees were dead (maybe due to overage or insects/fungi)
- 68.2 % of the trees with diameter above 10 cm belong to commercial timber species, 44.1 % to the most wanted timber species, and 4.9 % to Cedro Orán, which is the most wanted species (for the definition of the timber groups, see 4.3, Table 5).
- There are 7 m^2/ha of BA above the minimum logging diameter set by law (Annex 1), with a good healthy condition also, but excluding those bigger than 60 cm DBH (over mature, outliers).
- Regeneration between 5 and 10 cm DBH:
    - 679 trees/ha
    - 38.5 % belongs to timber species, 12 % to 'cebil moro,' 11 % to 'virarú,' and 4 % to 'cedro Orán.'

The values of BA reported in the Florestoona inventory before the fire incident in 2013 are lower than BA values from ProYungas, measured on a set of 47 one-hectare permanent plots (Blundo & Malizia 2009; Blundo et al. 2012). In their preliminary results, they report that the basal area of an intact Yungas forest is approximately 25 m^2/ha. However, the present case study corresponds to a typical open forest in the Selva Pedemontana de Yungas, which presents this condition due to overuse for more than 100 years (Eliano et al. 2009).

4.2 Mapping forest degradation

Figure 5 presents the workflow through which two supervised classifications of a SPOT6 image into four fire-severity strata (‘fully stocked,’ ‘burned,’ ‘severely burned,’ and ‘very severely burned’) were accomplished and then compared in order to test whether or not including UAV-derived metrics improves the precision of the classification, and reduces the number of necessary inventory plots for a target error. One of the classifications was trained with BA data from ground inventory (Scott & Gove 2002), and the other one with adjusted canopy cover index (ACCI) data. ACCI was formulated by the correlation of BA with forest horizontal and vertical structure variables estimated from UAV imagery analysis (for details, see 4.2.5). In both classifications, a part of the data from the ground inventory was used to train image classification, and the whole dataset from ground inventory was used to estimate classification errors. For the ACCI-based classification, an additional 20 UAV- image plots were located and calculated to support the classification.

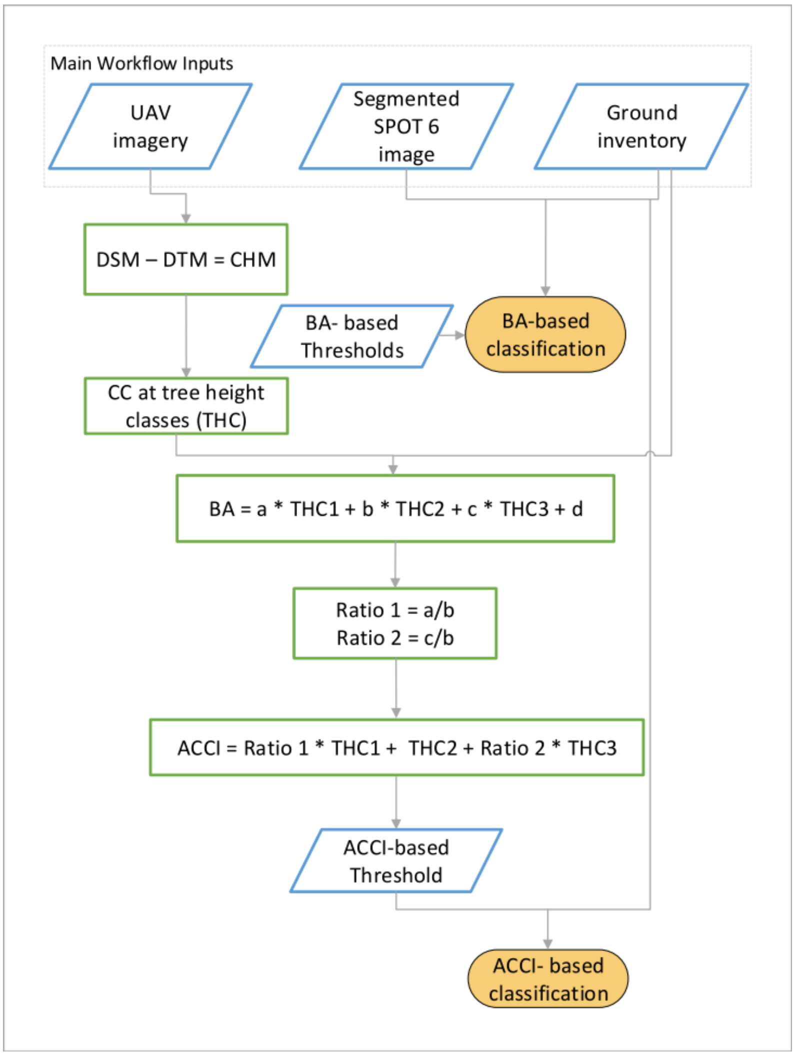


Figure 5: Workflow used to complete the two image classifications into fire-severity strata. Both outputs (BA-based and ACCI-based classifications) are classifications of the same SPOT6 image into four fire-severity strata based on the damage to forest stocks ('fully stocked,' 'burned,' 'severely burned,' and 'very severely burned') using two different input data.

4.2.1 Delineation of burned area

A first delineation of the area of interest was completed on a Landsat 8 scene from 19th December 2013 at 14:13 local time (Chuvieco & Kasischke 2007; Masek et al. 2008). Landsat 8 scene LC82300762013353LGN00 was downloaded from the United States Geological Survey webpage. The scene is ortho-rectified (Level -1 Product), with a processing level L1T using GLS2000 as a digital terrain model (DTM) resource for the correction. The expected circular error is 12 m with 90 % of confidence. Landsat 8 imagery has sensors to collect data at the wavelength and resolution shown in Table 2.

Table 2: Landsat 8 bands, wavelength and resolution. Bands 1 to 7 and 9 have 30 m/pixel resolution; band 8 has 15 m resolution; band 10 and 11, 100 m resolution, but resampled to 30 m. Source: www.landsat.usgs.gov.

Bands	Wavelength (micrometres)	Resolution (meters)
Band 1 - Coastal aerosol	0.43 - 0.45	30
Band 2 - Blue	0.45 - 0.51	30
Band 3 - Green	0.53 - 0.59	30
Band 4 - Red	0.64 - 0.67	30
Band 5 - Near Infrared (NIR)	0.85 - 0.88	30
Band 6 - SWIR 1	1.57 - 1.65	30
Band 7 - SWIR 2	2.11 - 2.29	30
Band 8 - Panchromatic	0.50 - 0.68	15
Band 9 - Cirrus	1.36 - 1.38	30
Band 10 - Thermal Infrared (TIRS) 1	10.60 - 11.19	100 * (30)
Band 11 - Thermal Infrared (TIRS) 2	11.50 - 12.51	100 * (30)

In the environment ArcGIS 10.3, three bands (5, 4, 3) were combined for RGB visualisation, with the purpose of strengthening the differences between vegetation and soil. A supervised image classification into two classes ('affected' and 'unaffected') was conducted to extract the fire perimeter, as shown in Figure 6.

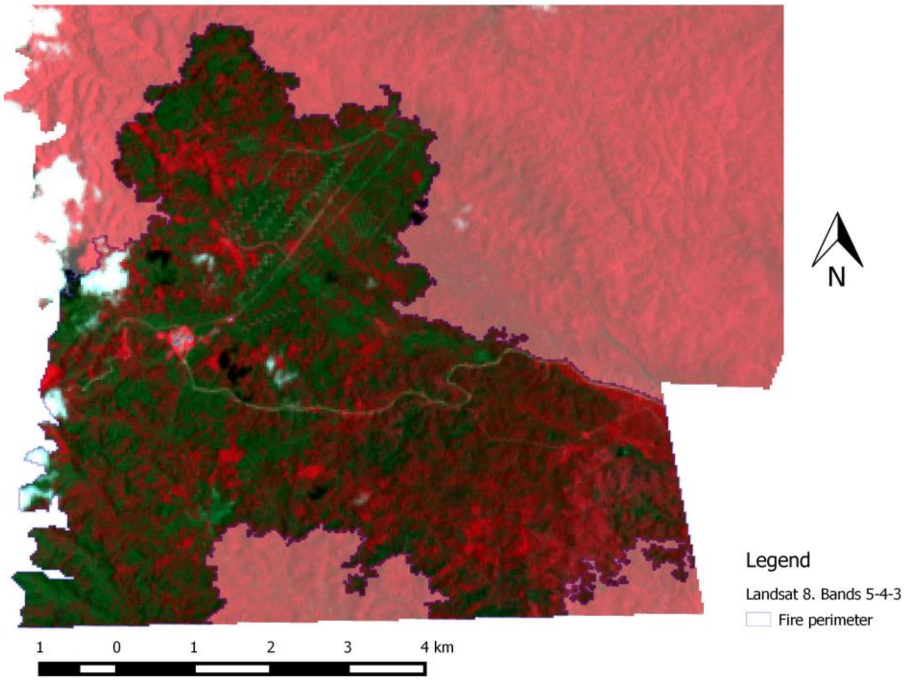


Figure 6: Fire perimeter determined on Landsat 8 scene from December 19th, 2013

4.2.2 *Ground inventory*

A pilot survey inventory of 24 plots in six transects along existing roads was conducted in August 2015 over the burned area delineated on the Landsat 8 scene. Tree species, DBH (with diameter tape), tree height (with Vertex IV and transponder T3 v.1.0), stem height, health, damage by fire, silvicultural class (mature, future crop tree, indifferent, or competitor), and observations of the plot and individual trees were recorded (see inventory protocol in Annex 2). The two-radii plot approach recommended by Balducci et al. (2012) to be used in Yungas (Figure 7), was adapted to the n-tree sampling (Jonsson et al. 1992). Circular concentric subplots of 300 m² for trees with DBH from 10 cm and lower than 30 cm, and of 1000 m² for trees with diameter from 30 cm were set. The inner subplot was adapted to 1000 m² when the number of trees in the inner plot was lower than eight. Regeneration was measured on a 25 m² plot centred on the east limit point of the outer subplot (Figure 7).

In order to achieve a stratified relative estimation error lower than 20% (based on BA), which is prescribed for inventories in Argentina (Balducci et al. 2012), a second survey was conducted in two stages (December 2015 and November 2016). In December 2015, 23 plots were randomly selected from a grid spaced every 500 m. A restriction of a maximal distance of 500 m from tertiary roads was established due to difficult access to the field. On the second stage, 30 plots were stratified randomly selected in order to reach remoter areas and prove the classification errors. In this final stage of the inventory, additionally to the previous protocol, 3 trees per plot ('reference trees,' in total 90 trees) were randomly selected and their northing (with compass) and distance (with vertex) from the centre of the plot were measured. These reference trees would have the double function of helping to relocate the plots and validate canopy height models (CHM) after further UAV imagery analysis.

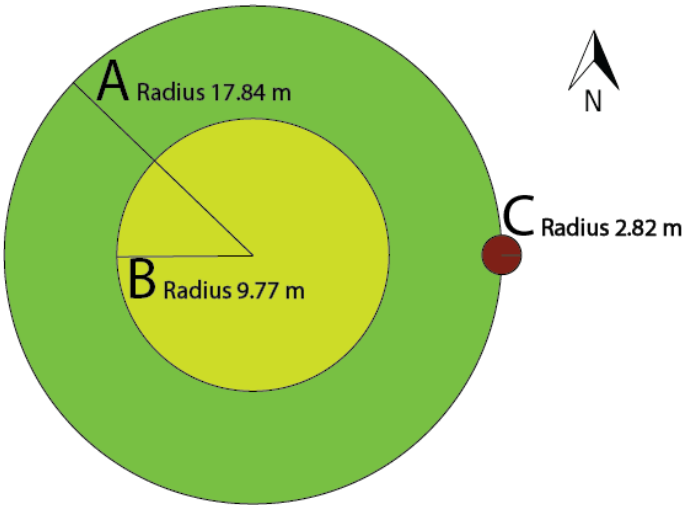


Figure 7: Plot design. ***A*** *is the outer subplot of 1000 m²for trees with DBH of 30 cm or more;* ***B*** *is the inner subplot of 300 m² for trees with DBH lower than 30 cm, and* ***C*** *is the regeneration plot of 25 m², Balducci et al. (2012). However, in this research the design was adapted to the n-tree sampling, adapting the inner subplot to 1000 m² when the number of trees in the 300 m² subplot was lower than eight.*

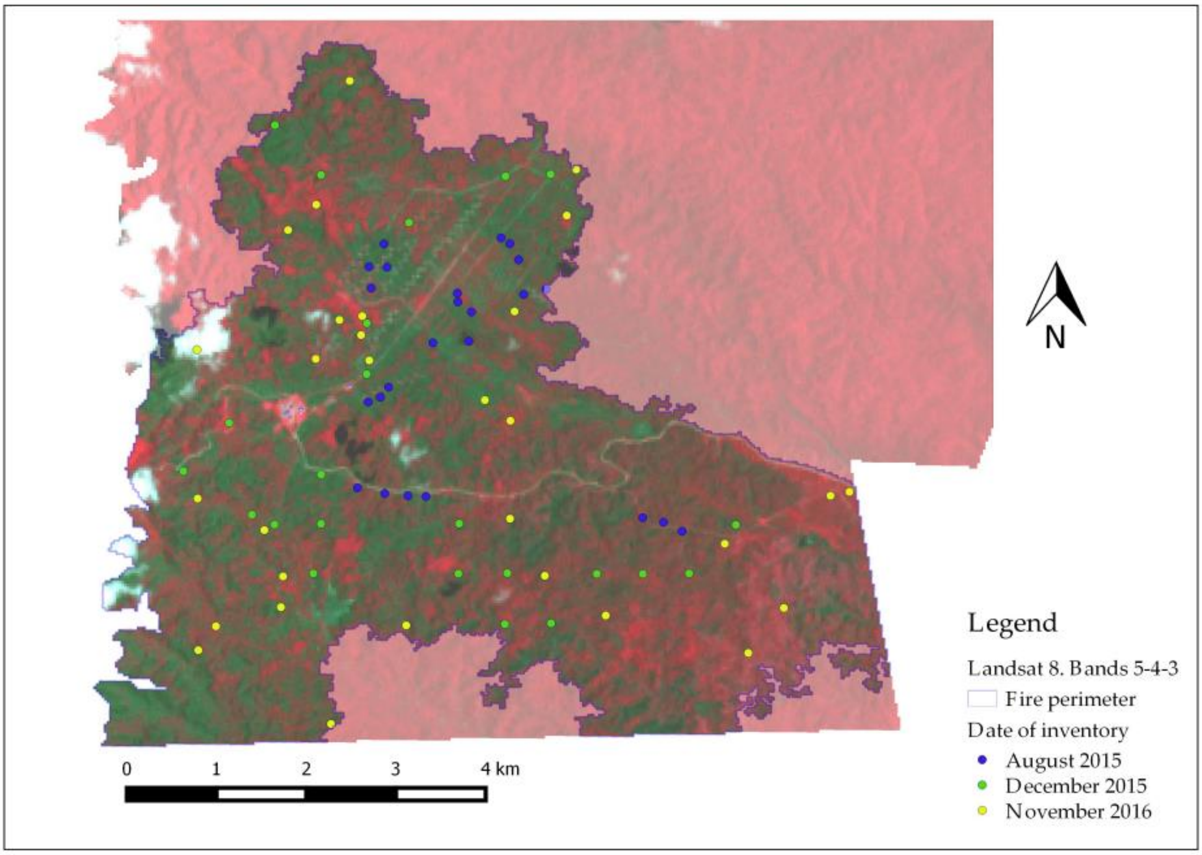


Figure 8: Location of the inventory plots for each of the phases of the inventory: August 2015 (blue, n:24), December 2015 (green, n:23), and November 2016 (yellow, n:30). In the background the delineation of the burned area over a Landsat 8 scene from December 19th, 2013.

4.2.3 *UAV Imagery acquisition*

UAV imagery was acquired in August and December 2015 using a fixed-wing UAV (eBee, SenseFly, Cheseaux-sur-Lausanne, Switzerland). In total, 31 flights were conducted, out of which two were discarded due to wrong GPS data attachment on the single images. Thus, 3,801 images were left covering 2,915 ha. That represents 74 % of the burned area in the cadastral field of Florestoona. All flights were completed under the requirements of the law of permanent contact to the aircraft (ANAC resolution 527/2015).

The camera used (Canon PowerShotS110, Canon Inc., Tokyo, Japan) was modified by the provider to take pictures in the near infrared (NIR), red, and green wavelength ranges. The fully-equipped UAV has a weight of approximately 700 g, and a flight autonomy of 40 minutes maximum. However, the actual duration varies based on the age of the batteries, air temperature, wind speed, and altitude. In this case, no flights longer than 25 minutes have been conducted. With the flight planning software *eMotion* 2.4 (SenseFly Ltd, Cheseaux-sur-Lausanne, Switzerland) field work for data acquisition was planned in advance by individual, or groups of, flights. Groups were arranged based on the time consumption to cover the full grouped areas in consecutive missions on the same day (between 11:00 and 14:00) to avoid differences on the imagery due to weather conditions, which would negatively affect image post-processing.

Counting with 3 batteries and 2 chargers, up to 6 flights per day were feasible, although many flights were cancelled due to strong wind (speed higher than 6 m/s) in order to benefit image post-processing (arching branches are conducive to low quality images, adding to the normal motion blur; [Nurminen et al. 2013]). Flights were planned to keep a constant altitude of 284 m aboveground, preferably parallel to altitude isolines. Landing and take-off areas were programmed on the field. Once take-off was assisted, the rest of the planning and the image acquisition were completed automatically. Emergency commands were given, when necessary, to abort landing, to push landing forward without ending mission, and to change flight altitude. This was possible by a permanent remote contact kept through an antenna plugged into the commanding computer with Windows OS. Flight speed was automatically adapted to 11 m/s by the autopilot. Image overlapping was set to 75 % in both directions (side and forward).

4.2.4 Photogrammetric processing

The images acquired by the UAV have been attached with coordinates from the autopilot and then further processed with the Structure from Motion (SfM) software Pix4discovery by Pix4D 3.1.22 (Burns & Delparte 2017). The software proceeds in several steps: interior and exterior camera calibration, image matching and optimisation (automatic aerial triangulation and bundle block adjustment), calculates a dense 3D-point-cloud (LAS file) and orthomosaic. Georeference of the scene was conducted directly based on GPS information attached to the picture files from the UAV-GPS device (Turner et al. 2014).

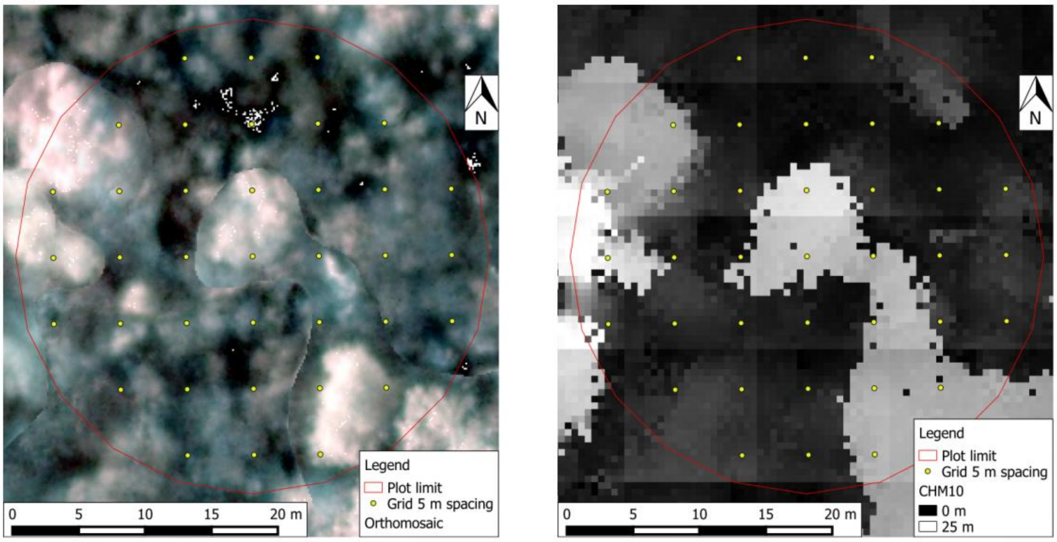
Point clouds were processed in the ArcGIS 10.3 environment to convert LAS dataset to raster files employing the void fill method ‘natural neighbour’ (ESRI 2015). A single digital surface model (DSM) and two DTMs were calculated: the DSM with 0.5 m/pixel of resolution, one DTM with 5 m/pixel of resolution (DTM5), and a second one with 10 m/pixel resolution (DTM10). For computational efficiency, all data were resampled to the same resolution of 0.5 m/pixel using the ‘nearest’ resampling method. This method is recommended when the output pixel size is smaller than the input, and each output pixel is related to a single input value (ESRI 2015). Two CHMs were calculated as a result of deducting the resampled DTMs from the DSM. One was calculated using the DTM5 (CHM5), the other using the DTM10 (CHM10). The accuracy of the CHMs were later compared against ground measurements of ‘reference trees’ heights (see 4.2.2; Nurminen et al. 2013; Iizuka et al. 2018).

4.2.5 Formulation of the adjusted canopy cover index

The adjusted canopy cover index (ACCI) was formulated to allow a satellite image classification to be conducted independently from the measurements on the field. Consequently, this classification was trained with forest attributes (tree height and canopy cover [CC]) estimated from the photogrammetric analysis of UAV imagery. However, since the error of forest inventories in Argentina are prescribed based on the deviation of BA per stratum, the correlation of BA to CC and tree heights needs to be considered. The simple estimation of CC, which is one of the selected variables to estimate forest degradation, would lack the influence of tree heights, which would also have an effect on forest stock. Since it is expected that CC from tall trees has a greater effect on BA than CC from shorter trees, forest vertical structure was first stratified into three tree height classes (THC):

- THC1: partial CC from trees with height between 5 and 9.99 m
- THC2: partial CC from trees with height between 10 and 19.99 m
- THC3: partial CC from trees of 20 m and higher

Due to the limitation of optical remote sensors to acquire data under dense canopy, partial CC at each tree height cannot be estimated automatically over the whole data set, but the calculations still need to be supervised, and often completed manually. Therefore, the calculations of canopy cover were completed in samples over a grid of points spaced every 5 m starting from the centre of the plot (Figure 9). 37 points per plot were established in the circular area of analysis of 1000 m^2. Tree heights were extracted from each of the CHMs (CHM5 and CHM10), and were assigned to a THC at each of the grid points. For each plot, percentage values of partial CC were obtained as shown in Formula 1. At every plot, both CHMs and the orthomosaics were visually inspected to identify pixelation (sudden contrast of low and high values), which often occurred in cases of dense CC. When a point of the grid was on a pixelated area, the wrong predictions of tree height were corrected manually by assigning them the canopy height value of the closest neighbours.



A B

*Figure 9: Grid of 5 x 5 m used for estimation of percentage CC per THC. Example plot area with a grid set on mosaic (**A**) and grid set on CHM (calculated from DTM of 10 m resolution; **B**). For both images the limit of the plot is marked on a red line.*

$$THC_i(\%) = \frac{AbTHC_i}{37} \times 100 \quad (1)$$

Where $THC_i(\%)$ is the percentage of canopy cover of the tree height class i; $AbTHC_i$ is the absolute number of the point from the grid at the tree height class *i;* 37 and 100 are the total number of points in the grid, and a correcting factor to get percentage results, respectively.

THCs are percentage values, and express the partial canopy cover related to a certain tree height class. TCHs' percentage canopy cover was then correlated to BA for all the 70 plots where both input data (ground inventory and AUV imagery) were available. The model is shown in Formula 2.

$$BA = a \times THC1 + b \times THC2 + c \times THC3 + d \quad (2)$$

Where BA is the basal area of the plot; a, b, c, and d are the constant coefficients of the independent variables; THC1, THC2, and THC3 are the independent variables, which express partial CC at every THC as percentage.

Coefficients 'a,' 'b,' and 'c' are a measure of the effect of the variables THC1, THC2, and THC3 for the prediction of BA (Sokal & Rohlf 1997). For example, assuming that the rest of the variables are constant, a change on one unit of THC1 will increase 'a' m^2 on the predicted value of BA. Since independent variable scales are identical (0 to 100), the impact of the tree height classes on BA can be directly compared (Fox 2008). In order to obtain an index which resumes the effect of tree height classes, two ratios were formulated at first (Formula 3 and Formula 4) to show the relative impact of the THC1 and THC3 in relation with THC2.

$$Ratio1 = \frac{a}{b} \quad (3)$$

$$Ratio2 = \frac{c}{b} \quad (4)$$

Taken from Formula 2, a, b, and c are the coefficients related to independent variables THC1, THC2, and THC3, respectively.

Those ratios were used to formulate the adjusted canopy cover index (ACCI), as shown in Formula 5:

$$ACCI = Ratio1 \times THC1 + THC2 + Ratio2 \times THC3 \quad (5)$$

Where ACCI is the adjusted canopy cover index; Ratio1 and Ratio2 are the ratios of coefficients from Formula 3 and Formula 4; THC1, THC2, and THC3 are the independent variables which express partial CC at every THC (in percentage).

ACCI was formulated as a variable closely related to canopy cover, but which additionally weighs partial CC from THCs by their influence on BA. It approaches the prediction of fire-induced damage, since it refers to horizontal and vertical structures of a stand, and their influence on BA.

This process was completed with data from the CHM10, since it was expected to give better predictions of tree heights than CHM5. It could be acquired for 70 plots out of the 77 plots of ground inventory. Three flights covering five of the plots had problems on the GPS data attachment during image processing, and could not be used. Two plots were located on the border of the mosaic, where image deformation is too big, and the data cannot be clearly interpreted. An additional 20 stratified randomly located UAV image plots were analysed in order to estimate their ACCI value.

4.2.6 Image classification

An orthorectified multispectral SPOT6 image taken on 26th October 2014 at 15:12 local time was acquired in order to conduct the two Nearest Neighbour Classifications. This image was selected for the analysis because it was the first SPOT6 image after the fire incident (November 2013) with an acceptable cloud cover (<2 %) on the area of interest. Multispectral SPOT6 orthorectified products have a resolution of 6 m for the band ranges blue, green, red, and NIR (Table 3). The Nearest Neighbour Classification consists of a multiresolution segmentation and a supervised classification, which were conducted with the software e-Cognition 9.2 (Strobl & Griesebner 2000; Frohn & Chaudhary 2008). This procedure demonstrated benefits, such as incorporating spectral and textural information, and therefore has been broadly used on environmental studies (Frohn & Chaudhary 2008). The scale parameter for segmentation was set to 10, image layers were all equally weighted, and heterogeneity criteria were set to 0.3 for shape and 0.5 for compactness. 12,991 polygons of an average of 3,036 m^2 from a total area of 3,944 ha were obtained.

Table 3: Multispectral SPOT6 bands, wavelength and resolution. Source: www.intelligence-airbusds.com.

Bands	Wavelength (micrometres)	Resolution (meters)
Band 0 - Blue	0.455 - 0.525	6
Band 1- Green	0.530 - 0.590	6
Band 2 - Red	0.625 - 0.595	6
Band 3 - NIR	0.760 - 0.890	6

4.2.6.1 *Thresholds of fire-severity*

In order to train the two image classifications, two set of thresholds were used to define fire-severity strata: one based on BA, and the other one based on ACCI. Strata of fire-severity were defined assuming that forest stocks were uniform before the fire. Therefore, low forest stocks were related to severe fire damage. This assumption was based on the 2008 inventory (Eliano et al. 2009), and on the fact that the area of interest is limited by altitude isoline of 700 m a.s.l., which is considered to be the upper limit of the phytogeographical area of Selva Pedemontana de Yungas (Brown et al. 2001). From the data of the 2008 inventory, the BA-benchmark of intact forest, from which thresholds were calculated, was set to 18 m^2/ha, and the ACCI-benchmark was set arbitrarily to 100.

From the benchmark, multi-thresholds were set in order to define the strata of fire-severity (Thompson et al. 2013; Morales-Barquero et al. 2014; Table 4 and Figure 10). The threshold of a 'fully stocked' forest was defined based on the recommendation for the sustainable management of native forests in the Yungas, where a minimum of two-thirds of the original BA (12 out of 18 m^2/ha) should be left after a regular logging (Balducci et al. 2012). According to those recommendations, a forest which faced a reduction of the forest stocks up to one third is able to recover the stocks in one intervention period (set to 20 years in Yungas [Balducci et al. 2012]), and therefore is not regarded as a degraded forest, based on the proposed definition. The other threshold values shown in Table 4 were also set as thirds of the benchmark. Additionally, the least stocked third was divided into two strata, with an ACCI value of up to 20, and one between 20 and 33. The ACCI threshold of 20 was set in order to consider the canopy cover of 20 %, which is a threshold for the legal definition of forests (Consejo Federeal del Medio Ambiente 2012). Then, in order to create two comparable sets of thresholds, the most degraded third of the BA-based classification was proportionally divided into two strata.

Table 4: Thresholds for the definition of degraded forest strata based on BA and ACCI.

Fire-severity strata	Range BA (m²/ha)	Range ACCI
Very severely burned	≤ 3.6	≤ 20
Severely burned	> 3.6 and ≤ 6	> 20 and ≤ 33
Burned	> 6 and ≤ 12	> 33 and ≤ 66
Fully stocked	> 12	> 66

Finally, two supervised classifications were conducted over the segmented SPOT6 image, using the two sets of fire-severity thresholds (based on BA and ACCI). To supervise the classification, segments (resulted from image segmentation), from ground and imagery plots, were assigned to classes. Samples of an additional stratum called 'bare land' were selected over roads and construction areas (houses, sheds). For the BA-based classification, samples were selected from the first 47 inventory plots. For the ACCI-based classification 64 samples were selected: 44 out of the 47 plots used for the BA-based classification (3 had to be excluded due to image blur), and the additional 20 UAV image plots. The rest of the 12,991 segments were assigned to the closest class, based on their similar texture and spectral data from the SPOT6 image, during the Nearest Neighbour Classification.

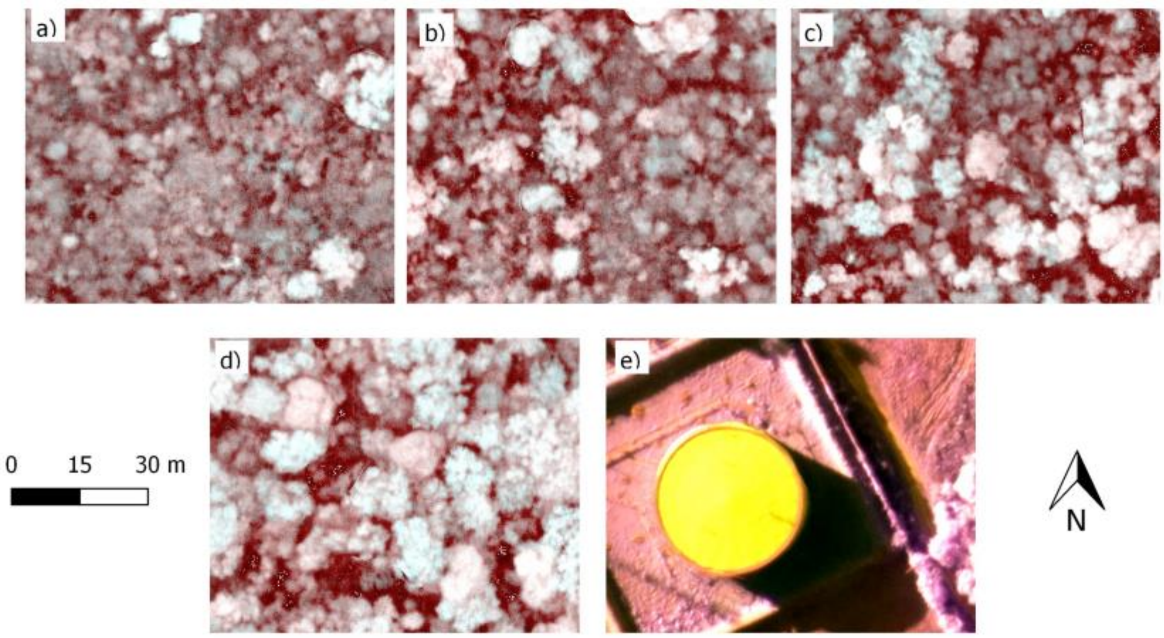


*Figure 10: UAV image view of the four fire-severity strata: very severely burned (**a**), severely burned (**b**), burned (**c**), fully stocked (**d**), and bare land with buildings (**e**). Mosaic band composite: NIR-green-red.*

4.2.6.2 *Comparison of BA-based and ACCI-based classifications*

In order to compare the accuracy of the two methodologies to stratify the forest, overall classification errors were calculated using the Cohen's kappa coefficient (k). This statistic uses a matrix of frequencies of predicted and actual stratum (based on BA-thresholds) to calculate the agreement between them (Bortz 1993; Watson & Petrie 2010). Standard error (SE) were calculated, and statistical difference between the k coefficients were assessed with a two sample Z-test at 95 % of confidence. Stratified estimation error (E) and relative stratified estimation error (E %) were calculated out of the BA from 76 plots (one of the 77 ground inventory plots was excluded due to being located outside the fire perimeter), based on Formula 6 and Formula 7 (Gaillard de Benítez & Pece 2014) for each of the classifications (BA-based and ACCI based).

$$E = \frac{S \times t}{\sqrt{n}} \tag{6}$$

Where E is the estimation error; S is the standard deviation of the BA from all the plots of the respective fire-severity stratum; t is the t-value with 95 % of confidence in a two-tailed test; n is the number of plots in the class.

$$E\% = \frac{E}{\bar{x}} \times 100 \tag{7}$$

Where $E\%$ is the relative estimation error; E is the estimation error; $\bar{x}$ is the average BA from all the plots in the class.

Finally, the number of plots necessary to achieve the target stratified BA-based estimation error of 20 %, to accomplish the prescription of the Argentinian law, were calculated with Formula 8 for each of the classifications.

$$n = \frac{t \times S}{0.2}^{2} \tag{8}$$

Where n is the number of plots to achieve the stratified estimation error of 20 % (0.2); t is the t-value with 95 % of confidence in a two-tailed test; S is the standard deviation of the BA from all the plots of the fire-severity stratum.

Statistical difference of mean BA among the strata were tested with the use of the Welch t-test on the statistics software *R* 3.4.2 for both BA-based and ACCI-based classifications. The Welch t-test can be used to compare mean difference in case the sample size of groups to compare are small and the variance is not homogeneous (Bortz 1993; Williamson 2008)

4.2.7 Validation of CHMs

The 'reference tree' heights measured on the ground were correlated with their direct predictions from CHMs (without correction on pixelated areas). It was done with the objective of assessing the accuracies of the automatic predictions of tree heights from CHMs at different degrees of canopy opening. Dead trees were eliminated from the analysis, since they were not properly detected by the cameras, and only live BA was counted in this research. The correlations of the tree heights measured on the field, and their estimations from CHM5 and CHM10, were conducted of three groups: (1) 'fully stocked,' (2) 'burned,' and (3) 'severely burned' (SB) together with 'very severely burned' (VSB). Mean absolute error (MAE), root mean squared error (RMSE), and coefficient of determination (r^2) were calculated for both CHMs and each fire-severity strata.

4.3 Additional description of fire-severity strata

Based on the results of the ACCI-based classification, in order to show the structure of the strata acquired with the proposed methodology, every stratum is described in terms of diameter at breast height (DBH) distribution, regeneration, species composition, number of live trees, future crop trees (FCT), and mature trees per hectare. Species composition is reported based on the classification proposed by Eliano et al. (2009), where species are grouped according to the value of their timber in 'most wanted,' 'wanted,' and 'indifferent' (Table 5).

Table 5: Local and species name of the most frequent species classified into groups of timber value (Eliano et al., 2009).

Local name	Species name	Value group
Cebil moro	*Anadenanthera colubrine* Brenan	Most Wanted
Cedro Orán	*Cedrela balansae* C.DC.	Most wanted
Lanza blanca	*Patagonula Americana* L.	Most wanted
Lapacho	*Tabebuia impetiginosa* Standl.	Most wanted
Palo amarillo	*Phyllostilon rhamnoides* Taub.	Most wanted
Palo blanco	*Calycophyllum multiflorum* Griseb.	Most wanted
Quina colorada	*Myroxylon peruiferum* L.f.	Most wanted
Urundel	*Astronium urundeuva* M.Allemão	Most wanted
Afata	*Cordia trichotoma* Arráb.	Wanted
Aguay	*Chrysophyllum gonocarpum* Engl.	Wanted
Arca	*Acacia visco* Lorentz	Wanted
Cascarón	*Cascaronia astragalina* Griseb.	Wanted
Horco cebil	*Parapiptadenia excelsa* Burkart	Wanted
Laurel blanco	*Ocotea puberula* Nees	Wanted
Lanza amarilla	*Terminalia triflora* Lillo	Wanted
Mora	*Chlorophora tinctoria* Gaudich.	Wanted
Pacará	*Enterolobium contortisiliquum* Morong	Wanted
Quina blanca	*Lonchocarpus lilloi* Burkart	Wanted
Roble	*Amburana cearensis* A.C.Sm.	Wanted
San Antonio	*Myrsine laetevirens* Arech.	Wanted
Tarco	*Jacaranda mimosifolia* D.Don	Wanted
Tipa or Tipa blanca	*Tipuana tipu* Kuntze	Wanted
Tipa colorada	*Pterogyne nitens* Tul.	Wanted
Virarú	*Ruprechtia laxiflora* Meisn.	Wanted
Coronillo	*Gleditsia amorphoides* Taub.	Indifferent
Duraznillo	*Ruprechtia apetala* Wedd.	Indifferent
Espinillo	*Pithecellobium scalare* Griseb.	Indifferent
Guayabil	*Saccellium lanceolatum* Bonpl.	Indifferent
Lanza	*Phyllostylon rhamnoides* Taub.	Indifferent
Laurel negro	*Nectandra pichurim* Kunth	indifferent
Lecherón	*Sebastiania brasiliensis* Spreng.	Indifferent
Mato	*Eugenia mato* Griseb.	Indifferent
Palo borracho	*Ceiba chodatii* Ravenna	Indifferent
Palo Barroso (molle)	*Blepharocalyx salicifolius* O.Berg	Indifferent
Pata	*Agonandra excels* Griseb.	Indifferent
Quebrachillo	*Acanthosyris spinescens* Griseb.	Indifferent

4.4 Establishing forest management units

Based on the applied segmentation, 12,991 features (stands) of an average of 3,036 m^2 from a total area of 3,944 ha were obtained. Those were classified into the five strata ('bare land,' 'very severely burned,' 'severely burned,' 'burned,' and 'fully stocked'). All features of the stratum 'bare land,' which were not related to forest land (built up areas and roads), were deleted to conduct this part of the analysis. Therefore, 12,353 features from the segmented SPOT6 image were left reaching 3,865.6 ha, at an average of 3,129 m^2 per feature.

Because the resulting stands were too small to plan and implement rehabilitation measures, the establishment of forest management units (FMUs) was necessary. Therefore, site–scale FMUs were established via clustering of areas with similar conditions of forest stocks to be managed together (Oregon State University 2017). The identification of clusters was performed based on ACCI values using the Hot Spot Analysis (Getis-Ord Gi*). Each feature from the image segmentation took the value of the median ACCI of its stratum (Table 6). As a first step, as recommended by Noce et al. (2016), the existence of global spatial autocorrelation was tested with the Moran's *I* coefficient, and the identification of local clusters was completed by the use of the Hot Spot Analysis (Getis-Ord Gi*). As a result of this analysis, hot and coldspots were identified and mapped. Coldspot areas are clusters with significant aggregation of features of low values of ACCI, and should be dedicated to intensive forest rehabilitation techniques, such as intensive enrichment planting (EP), whereas hotspots are areas aggregating features of high values of ACCI, for which less intensive rehabilitation techniques, such as thinning, might be sufficient. In the remaining areas, where AACI values were randomly distributed, a conventional approach to plan management should be based on experts' knowledge. In the process of establishing FMUs, homogeneous areas smaller than 5 ha were 'eliminated' (aggregated to the biggest neighbouring cluster), since they were considered too small for the management plan (pers. comm. with Florestoona general manager).

Table 6: ACCI-based thresholds used to define fire-severity strata.

Fire-severity strata	Range of ACCI value	Median ACCI
Very severely burned	≤ 20	10
Severely burned	> 20 and ≤ 33	16.5
Burned	> 33 and ≤ 66	50
Fully stocked	> 66	83.5

4.4.1 Moran's I Analysis

Through clustering, features aggregated with others of the kind, of low or high value (cold or hotspots), can be identified. Based on Hartigan (1975), those clusters are regions which exhibit high densities separated from areas with low densities of a phenomenon. In this context, isolated features showing large or low values are considered outliers (Noce et al. 2016). Moran's *I* is the most known and used coefficient to determine global spatial autocorrelation testing if the features are either clustered, randomly distributed, or disperse (Prasannakumar et al. 2011; Paradis 2017). The algorithm used for its calculation is presented in Formula 9, and Formula 10:

$$I = \frac{n}{S_0}\frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad (9)$$

where *I* is the Moran's coefficient; w_{ij} is a symmetric one/zero spatial weight matrix, with one for all links defined as being within distance 'd' of a given *i*; all other links are zero, including the link of *i* to itself; *n* is the number of features in the full dataset; S_0 is the sum of all w_{ij}:

$$S_0 = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij} \qquad (10)$$

Moran's *I* coefficient varies between 1 (complete spatial autocorrelation) and -1 (total spatial dispersion). A zero value indicates random distribution. The observed *I* coefficient is compared with the expected coefficient in a complete random environment, and the significance of this autocorrelation is estimated by its z-score (Formula 11).

$$z\_score = \frac{I - E(I)}{\sqrt{VarI}} \tag{11}$$

4.4.2 *Hot Spot Analysis (Getis-Ord Gi*)*

Once a data set has demonstrated to be distributed by clusters, hotspot analyses are used to identify those clustered features. Hotspot analyses are used to estimate the overabundance of certain phenomenon, e.g. crime, disease surveillance, and species richness (Nelson, 2008, Fei, 2010, Vadrevu et al. 2013). The software ArcGIS 10.3 (ESRI 2015) has the built in functionality *Hot Spot Analysis (Getis-Ord Gi*)* to identify clusters, based on Gi* spatial statistics (Getis & Ord 1992; Ord & Getis 1995). Getis & Ord (1992) developed those statistics conducting an analysis which estimates the z-scores and p-values to reject or not reject the null hypothesis that the features are arranged under complete spatial randomness. Therefore, hotspot analysis indicates whether the spatial aggregation of a certain group of features responds to a random distribution or if there is a pronounced clustering of some high or low values. This methodology analyses feature by feature (classified segments from image segmentation), estimating GI* statistic for the group of values which are within a distance (d) from the feature *i*. The observed Gi* statistics for the feature *i* are compared with the expected Gi* statistics if the same values of the whole dataset were randomly distributed (Formula 12).

$$G_i^*(d) = \frac{\sum_j w_{ij}(d)\, x_j}{\sum_j x_j} \tag{12}$$

Where w_{ij} is a symmetric one/zero spatial weight matrix, with one for all links defined as being within distance d of a given i; all other links are zero, including the link of i to itself. The numerator is the sum of all x_j within d of i. The denominator is the sum of all x_j.

Based on that expression, and in a scenario of complete randomness, the expected Gi* value can be estimated (Formula 13):

$$E(G_i^*) = \frac{\sum w_{ij}(d)\, E(X_j)}{\sum X_j} \tag{13}$$

Where $E(G_i^*)$ is the expected value of Gi* in a scenario of complete randomness; X_j is a random value given to the feature j.

From the observed Gi* and expected G* value, the z-score for each feature is estimated by Formula 14.

$$Z_i = \frac{G_i^*(d) - E(G_i^*)}{\sqrt{VarG_i^*(d)}} \tag{14}$$

Where $G_i^*(d)$ is the observed value of the feature i; $E(G_i^*)$ is the expected value of Gi* in a scenario of complete randomness; $VarG_i^*(d)$ is the variance of the Gi* values of all features in a distance d.

Every feature is statistically analysed to obtain a p-value and z-score to estimate the aggregation significance (90, 95, and 99 %) for hot and coldspots. When z-scores are higher than 1.65 or lower than -1.65, aggregation is considered to be statistically significant (with 90 % of confidence or more; Table 7). Table 7 is theoretical for the case that a 'False Discovery Rate' (FDR) is not applied. However, FDR was used in this analysis in order to reduce statistical error Type I (Ord & Getis 2001), which might be abundant due to the spatial dependency of neighbouring features. Consequently, applying FDR, the weakest clustered features are considered 'randomly distributed,' conducting a more conservative analysis. More details of this analysis can be found in Benjamini & Hochberg (1995) and the tool reference of ArcGIS 10.3 (ESRI 2015).

Table 7: Gi z-scores values of the features and confidence of the assignment to clusters for hot and coldspots.*

Cluster	**Gi* z-scores**	**Confidence**
Hotspot	> 1.65	90 %
	> 1.96	95 %
	> 2.58	99 %
Coldspot	< -1.65	90%
	< -1.96	95%
	< -2.58	99%

As shown in Formula 12, Formula 13, and Formula 14, a distance threshold (d) must be established. This distance defines how many (and which) features will be included in the analysis. The larger the number of features, the more constant the Gi* value for neighbouring features, since more features overlap in the estimation of their Gi* value. As the distance set for the analysis increases, hot and coldspots tend to be larger (Nelson, 2008). Therefore, it is recommended to use a larger neighbourhood for detection when larger hotspots are of interest.

The distance threshold is the maximum distance for which the features are related under certain criteria (Getis & Ord 1992; Noce et al. 2016). Most of the researches are based on arbitrary distance thresholds (Nelson, 2008), since much knowledge of the ecosystem dynamics is necessary to decide on an optimal distance threshold, and most of the time it is not available. In this research, in accordance with Nelson & Boots (2008) and Noce et al. (2016), a multi-scale analysis was conducted in order to overcome the limitation of applying only one threshold distance. Every feature was analysed in a radius of 178, 252, 309, and 357 m, corresponding to 10, 20, 30, and 40 ha of perfect circled neighbouring areas, respectively. Those distances were selected after experts' inquiry, who stated that between 10 and 40 ha would be optimal sizes for the formation of FMUs in Yungas cloud forest. Hot Spot Analysis (Getis-Ord Gi*) uses feature centroids in distance computations, therefore the given threshold areas are approximated, since final area depends on the size and shape of the neighbouring features.

4.4.2.1 Additional processing

Since the final aim of the applied clustering is to establish meaningful FMUs, all features smaller than 5 ha were eliminated from the resulting map. Even if 10 ha would be the minimum area for a practioner's management unit, homogeneous areas between 5 and 10 ha were also still considered as potentially manageable, if they were close to a bigger FMU. When eliminating clusters smaller than 5 ha, these areas were included into the biggest neighbouring cluster (regardless of the type of cluster it was). Finally, the achieved map was overlaid on the original map of the classification in order to extract the composition (the spatial distribution of fire-severity strata) of each cluster.

4.4.3 *Landscape connectivity analysis applied to FMUs*

'Landscape connectivity determines which proportion of the total habitat area can be reached by, and is available for, an organism located in a particular point in the landscape' (Saura et al. 2011). It contributes to pollination, seed dispersal, gene flow, and wildlife migration and breeding, among other functions. Therefore, the impacts on landscape connectivity of the possible activities planned in the FMUs were analysed. The analysis was conducted with the software CONEFOR Sensinode 2.2 (CS22), which was developed at the Polytechnic University of Madrid (Saura & Torné 2009). Since this analysis identifies, ranking-wise, the most relevant stands for landscape connectivity, the resulting map was used to identify which of those stands would be compromised on FMUs with intensive rehabilitation techniques (coldspots). Therefore, CS22 output supports decision makers in planning adaptive management based on the ecological importance of the stands.

In this research, the analysis was applied only on 'fully stocked' stands, based on the ACCI-based classification, because they are supposed to have the highest contribution on landscape connectivity. Therefore, to begin, a file containing only 'fully stocked' stands was established, from which further steps were derived. The statistics were performed based on two theoretical seed dispersal distance thresholds (178 m and 357 m). Those distances were chosen arbitrarily because information about seed dispersal distances is scarce, but the chosen distances are on the expected range of seed dispersal distance by several dispersion types (autochory, anemochory, zoochory; Vittoz & Engler 2007). Furthermore, they are, in this research, the shortest and largest distances from the multi-scale analysis for the establishment of FMUs. In this context, two 'fully stocked' stands separated by more than 178 m or 357 m would not be regarded as connected, and the seed dispersal would not reach all the areas between them.

Several calculations of functional indices (metrics) are based on habitat sizes and distance between habitats to quantify the contribution of the individual habitat to the overall landscape connectivity (Saura & Torné 2009). The Integral Index of Connectivity (IIC) was chosen from the collection of available metrics, since it is appraised to be the best for integrating both habitat area and habitat connectivity (Pascual-Hortal & Saura 2006). The ranking of node (name given to the stands or habitats) importance is calculated comparing two measures of landscape connectivity: including and not including the node being analysed (Formula 15, and Formula 16).

$$\mathrm{dM}\ (\%) = 100\ \times \frac{M - M_{after}}{M} \tag{15}$$

$$Var\mathrm{M} = M - M_{after} \tag{16}$$

Where M is the landscape connectivity index value when all the nodes are present in the landscape, and M_{after} is the overall index value after the removal of that individual node from the landscape. VarM is the delta of the connectivity before and after excluding the node being analysed.

IIC calculations are presented in Formula 17. There it becomes obvious that the closer the stands are (fewer links are necessary to reach other stands), the more important the contribution of the stand on landscape connectivity.

$$IIC = \frac{\sum_1^n \sum_1^n \frac{a_i\, a_j}{1 +\ nl_{ij}}}{A_L^2} \tag{17}$$

Where a_i is the area of each stand and nl_{ij} is the number of links in the shortest path between stands i and j. For stands that are not connected, the numerator in the sum equals zero. When $i = j$ the nl_{ij} = 0 (no links needed to reach a certain stand from itself). A_L is the total landscape area.

The software CS22 needs two input files: the node file and the connection file. The node file contains a list of the habitat nodes in the landscape and its area. The connection file shows the Euclidean distance of the links between every possible combination of nodes. Both of the files were obtained from the 'Conefor inputs' plugin available on the environment QGIS 2.10 (Free Software Foundation Inc., Boston, USA).

Overlaying the resulting map of habitat contribution to landscape connectivity with the ones from FMUs (at distance thresholds 178 m and 357 m) shows how many and which of the most important stands for landscape connectivity are compromised on coldspots, which would be primarily used for intensive enrichment planting measures.

4.5 Enrichment planting in Florestoona

An enrichment planting (EP) project started in Florestoona forest in 2004, aiming to assess species growth, different designs (group and strip), and species association (monospecific or mixed-species EP). However, it was done without experimental design or statistical rigor, therefore the interpretation of the results must be cautious. Furthermore, the experiments of EP in a native forest conducted in Florestoona are one of the few conducted in the Argentinian Yungas. Those were done with the species 'toona' (*Toona ciliata* M. Roem., Meliaceae), 'tipa' (or 'tipa blanca,' *Tipuana tipu* Kuntze, Fabaceae), and 'paraíso' (*Melia azedarach* L.; Meliaceae). The closest well-known experiment was carried out by the National Institute of Agricultural Technology (INTA) in their experimental station (EEA) Yuto with the species 'toona,' 'tipa colorada' (*Pterogyne nitens* Tul., Fabaceae), and 'paraíso' among others (del Castillo et al. 2011). In contrast with Florestoona, 'tipa blanca' was not planted, but a close native species called 'tipa colorada.'

In order to test the preliminary results of the EP conducted in Florestoona, a ground inventory was conducted on blocks (groups of EP areas with similar characteristics; Figure 11). The assessment of many of the experimental EP areas was limited due to the damage by the mixed-severity fire of November 2013, affecting, to different degrees, the potential development of the trees. Therefore, EP areas with evident fire damage in the core of the enrichment planting area were excluded from the analysis. The ground inventory was carried out based on blocks formed from: (1) year of plantation, (2) species composition, (3) EP design, and (4) tree line orientation.

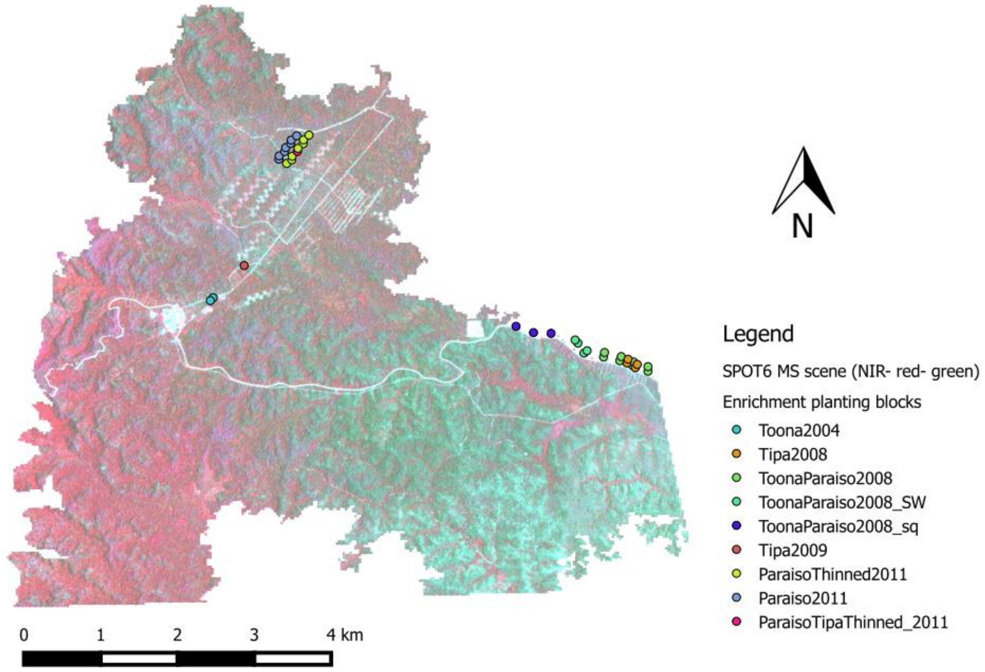


Figure 11: Location of the EP areas. Colours relate to blocks as shown in legend. Background map shows the area affected by the mixed-severity fire on November 2013 on a SPOT6 scene.

Table 8 shows the characteristics, and Figure 11 the location, of the EP areas. The inventory was conducted in two stages: the first one in August 2015, when the blocks Toona2004, Tipa2008, ToonaParaiso2008, ToonaParaiso2008_SW, ToonaParaiso2008_sq, and Tipa2009 were measured; on the second stage, in November 2016, the rest of the blocks were measured. The measured plots were located in the core of the EP areas, leaving two border lines. Those border lines showed an evident lower growth, and the objective of this inventory was to measure the potential of the species. The locations of the inventory plots in EP areas are shown in the sketches of strip EP (Figure 12) and group EP (Figure 13), separately. Strips were between 5 and 7 lines wide and ranged from 100 to 300 m long (Figure 12). In strip EP with 5 lines, the measurements were carried out on the 3 central lines, leaving only one border line at each side. Groups consisted of 13 lines (distanced by 3 m between them) along the road direction, and nine lines (distanced by 4 m between them) perpendicular to the road (Figure 13). In all cases, a buffer strip of 3 m wide surrounded EP areas.

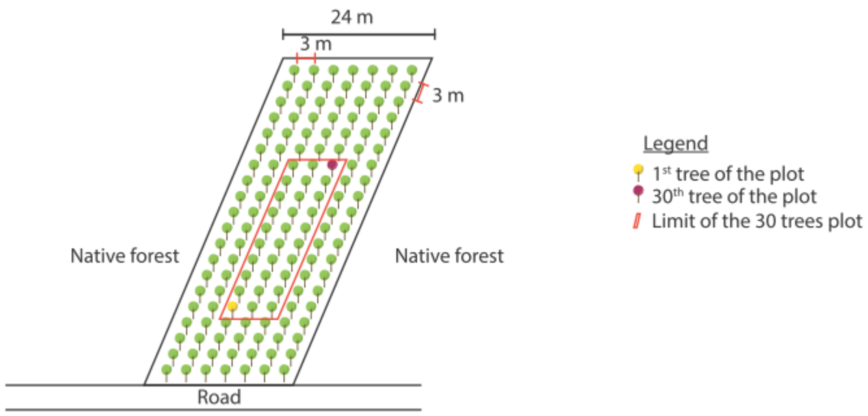


Figure 12: Design of the enrichment planting in strips and sketch of the location of the plots. The planting distance is 3 m between lines and 3 m between trees in the line. Native forest surrounds the strip, but a buffer area of 3 m is left from the last line of the EP in order to allow transit of tractor for silvicultural measures. The length of the EP varies from one to another EP area from 100 to 300 m.

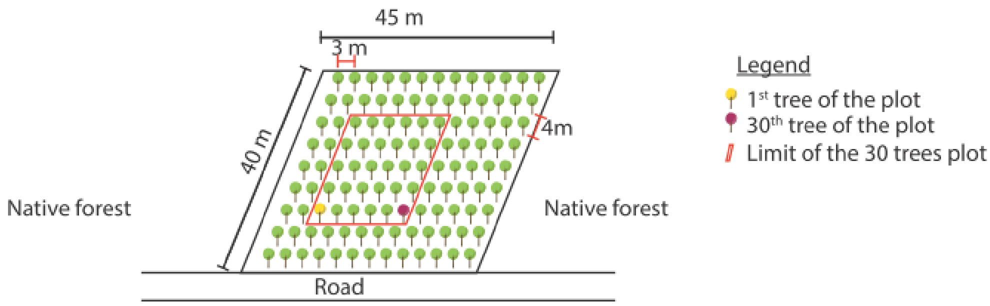


Figure 13: Design of the enrichment planting in groups and sketch of the location of the plots. The planting distance is 3 m between lines and 4 m between trees in the line. Native forest surrounds the strip but a buffer area of 3 m is left from the last line of the EP in order to allow transit of tractor for silvicultural measures.

The blocks Toona2004, and all the blocks planted in 2008, have been managed with a low thinning in the winter of 2010, while two out of the three EP of 'paraíso,' planted in 2011 (ParaisoThinned2011, and ParaisoTipaThinned2011), have been managed with a low thinning two weeks before the inventory (during spring). Aiming to measure the intensity of the low thinning, the stocks of the thinned block (ParaisoThinned2011) with the block Paraiso2011 were compared, but drawing conclusions about the thinning effect doesn't seem possible in such a short term. The only blocks which have not been intervened with thinning measures at the time of the inventory were Tipa2009 and Paraiso2011.

Table 8: Description of the blocks of enrichment planting.

Block id	Species	Planting date	Enrichment design	Spacing (m)	N° of plots measured	Inventory date (N° of growth periods)	Tree lines orientation
Toona2004	Toona	2004	Group	4 x 4	2	August 2015 (11)	SW - NE
Tipa2008	Tipa	2008	Strip	3 x 3	4	August 2015 (7)	N-S
ToonaParaiso2008	Toona & paraíso	2008	Strip	3 x 3	8	August 2015 (7)	N-S
ToonaParaiso2008_SW	Toona & paraíso	2008	Strip	3 x 3	4	August 2015 (7)	SW - NE
ToonaParaiso2008_sq	Toona & paraíso	2008	Group	3 x 3	3	August 2015 (7)	N-S
Tipa2009	Tipa	2009	Group	3 x 3	1	August 2015 (6)	NW - SE
ParaisoThinned2011	Paraíso	2011	Group	4 x 3	7	November 2016 (5)	NW - SE
Paraiso2011	Paraíso	2011	Group	4 x 3	7	November 2016 (5)	NW - SE
ParaisoTipaThinned2011	Paraíso & Tipa	2011	Group	4 x 3	1	November 2016 (5)	NW - SE

For all the cases, pruning was practiced at the second and fourth year after plantation, and mortality rate patches were replanted with several species, without any pattern. Consequently, the participation of those species is heterogeneous. In all cases, they represent less than 1 % of the measured trees. Therefore, the results are reported only from the main species used in the experiments: 'toona,' 'tipa,' and 'paraíso.'

30 trees were observed and measured per plot, for which species name, stem height, total height, DBH, evidence of plague attack, fire damage, evidence of logging (stumps), if the plant was a regrowth or original sapling, and other observations were recorded (inventory sheet is shown on Annex 3). For the plots, a sketch of the plantation spacing, tree line direction, and location of the first tree measured were made in the field. The location of the first tree (or stump) were recorded with differential GPS every second for five minutes (300 records, approximately).

4.5.1 Statistical Analysis

Several comparisons were made to test statistical differences in the mean DBH growth of the species based on species composition, design, and orientation of planting lines. Welch t-tests on the R statistics environment and result graphs were developed with the library *Matplotlib* from the script-based software Python 3.6 (Python Software Foundation, Beaverton, USA).

Formula 18 shows the calculations of mean annual increment (MAI) in DBH to compare blocks of the same species but different age (Bowers et al. 2013).

$$MAI = \frac{DBH}{Age} \tag{18}$$

Where DBH is the average diameter of the trees in the plot and 'Age' is the number of complete growing periods of the trees.

Comparisons made:

1. Species growth in the blocks planted in 2008. Comparison of the means of average growth of DBH between the species planted in the blocks ToonaParaiso2008, ToonaParaiso2008_SW, ToonaParaiso2008_sq, and Tipa2008.
2. Species growth in monospecific EP. Comparison of the means of maximum, minimum and average DBH-MAI between the species planted in the blocks Paraiso2011, ParaisoThinned2011, Toona2004, Tipa2008, and Tipa2009.
3. Mean growth between 'toona' in monospecific EP and 'toona' in mixed-species EP. Comparison of the means of average DBH-MAI between the block Toona2004, and the blocks ToonaParaiso2008, ToonaParaiso2008_SW and ToonaParaiso2008_sq.
4. Mean growth between 'paraíso' in monospecific EP and 'paraíso' in mixed-species EP. Comparison of the means of maximum, minimum, and average DBH-MAI between the blocks Paraiso2011 and ParaisoThinned2011, and the blocks ToonaParaiso2008, ToonaParaiso2008_SW and ToonaParaiso2008_sq.
5. Planting line orientation effect on the species 'toona' and 'paraíso' in the blocks planted in 2008. Comparison of the means of maximum, minimum, and average DBH per species between the block ToonaParaiso2008_SW, and the blocks ToonaParaiso2008 and ToonaParaiso2008_sq.
6. Planting line orientation effect of the blocks Tipa2008 with Tipa2009. Comparison of the means of average DBH-MAI. Since only one plot in the block Tipa2009 was measured, no comparison of means was conducted.
7. Design effect on the species 'toona' and 'paraíso.' Comparison of the means of DBH-MAI between the blocks ToonaParaiso2008_sq, Paraiso2011, ParaisoThinned2011, and Toona2004, and the blocks ToonaParaiso2008 and ToonaParaiso2008_SW.

In cases where the tree to be measured was not present, it was recorded as 'fail' for the estimations of survival factor (Formula 19). Survival factor represents the percentage of trees left after mainly natural mortality, fire-caused mortality, and thinning.

$$Survival\ factor_i(\%) = \frac{Live\ trees_i}{30} \times 100 \tag{19}$$

Where $'Live\ trees_i'$ is the number of live trees in the plot; 30 and 100 are constant values related to the total number of trees in the plot and a correcting factor to get percentage results, respectively.

5 Results

5.1 Mapping forest degradation

5.1.1 UAV image acquisition

Approximately 74 % of the burned area in Florestoona (2915 ha) was covered with unmanned aerial vehicle (UAV) flights, with a ground resolution of 11.78 cm/pixel, even though it was planned for 10 cm/pixel. This small variation might be due to the low precision of the available digital terrain model (DTM) on the flight planning software (eMotion 2.4), terrain altitude variations on the same flight line, and errors on GPS positions. 18 orthomosaics were created and saved as *geotif* images. During image processing, for 2-D bundle adjustment, an average of 0.42 key points per square meter were used, and 0.19 key points per square meter for 3-D bundle adjustment. Point cloud densification was obtained with an average of 8.32 points per square meter.

5.1.2 Photogrammetric processing

From the exported point clouds, 18 las-datasets were created. DTM5, DTM10, and digital surface model (DSM) were calculated. The two canopy height models (CHM5 and CHM10) were calculated from the same DSM and the respective DTMs (DTM5 and DTM10). At a constant DSM (with 0.5 m/pixel resolution), small differences between the CHMs were observed in areas of open canopy. A broader filter improves the accuracy of DTM, since the likelihood of selecting low points related to terrain (and not to shrubs or low canopy points) is increased. In Figure 14, CHM5 and CHM10 profiles along a central transect from the west to east of the plot are shown. The red arrow on Figure 14a shows a predictable error on the CHM5, where an abrupt change of canopy height on the model is evident. In Figure 15, this error is explained with more detail.

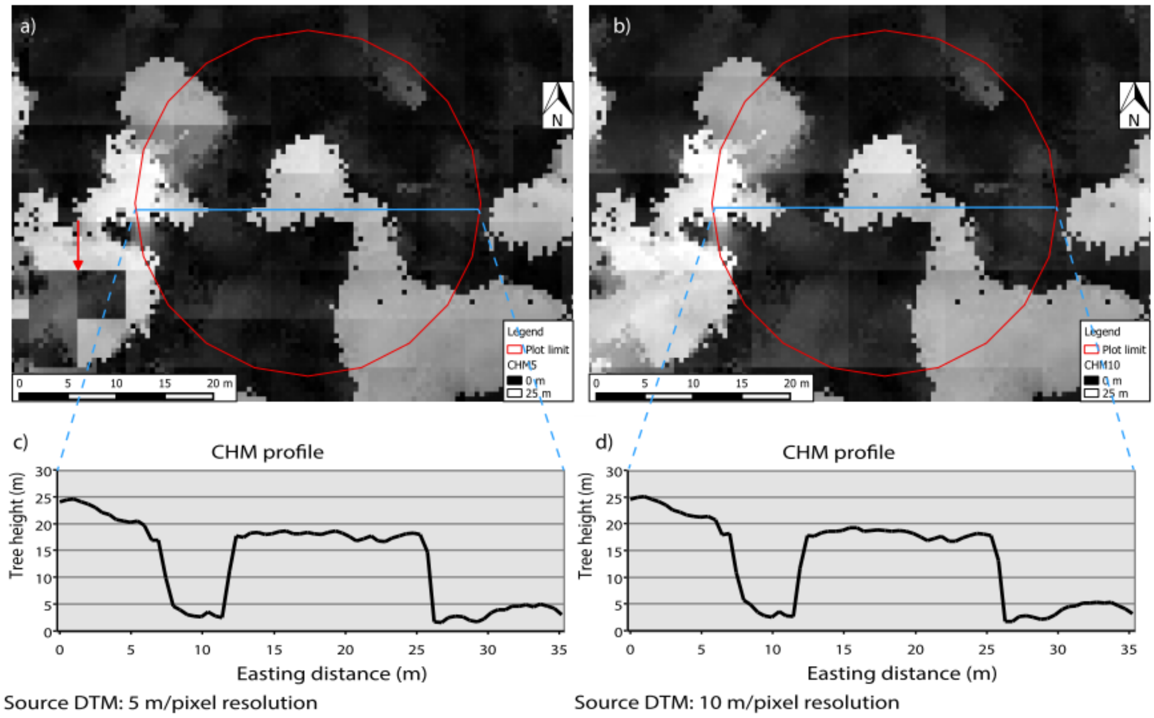


*Figure 14: CHM with 0.5 m/pixel resolution, calculated from digital terrain model with 5 m/pixel resolution (CHM5; **a**), and from DTM with 10 m/pixel resolution (CHM10; **b**). Red circle shows the limit of an example plot of 1000 m². Blue lines on **a** and **b** show the location of the CHM profiles shown on **c** and **d**. Small differences can be appreciated on the results inside the plot area, although the red arrow on **a** points to a pixelation-related error on the calculation of the CHM5.*

Figure 15 shows, in detail, the error highlighted in Figure 14. A transect of 30 meters along a pixelated area is analysed on different perspectives over each of the CHMs. First of all, on Figure 15a and Figure 15b, CHM5 and CHM10 of the same area are shown. Figure 15c shows the profile of the calculated CHM5. Every five meters, a change on the DTM5 (used for the calculation of CHM5) causes bigger or smaller differences in comparison with the CHM10 shown in Figure 15d. The greatest difference between the profiles is presented in the range of easting distance of 15 meters and 25 meters from the beginning of the transect. It is coincident to the point cloud, where no low key-points were obtained during image matching on these distances (Figure 15e and Figure 15f). These differences are due to dense canopy obstructing the terrain above this area. This error could be solved satisfactorily using the greater spacing while calculating DTM (10 m instead of 5 m) from the point cloud, since it allowed the selection of low points.

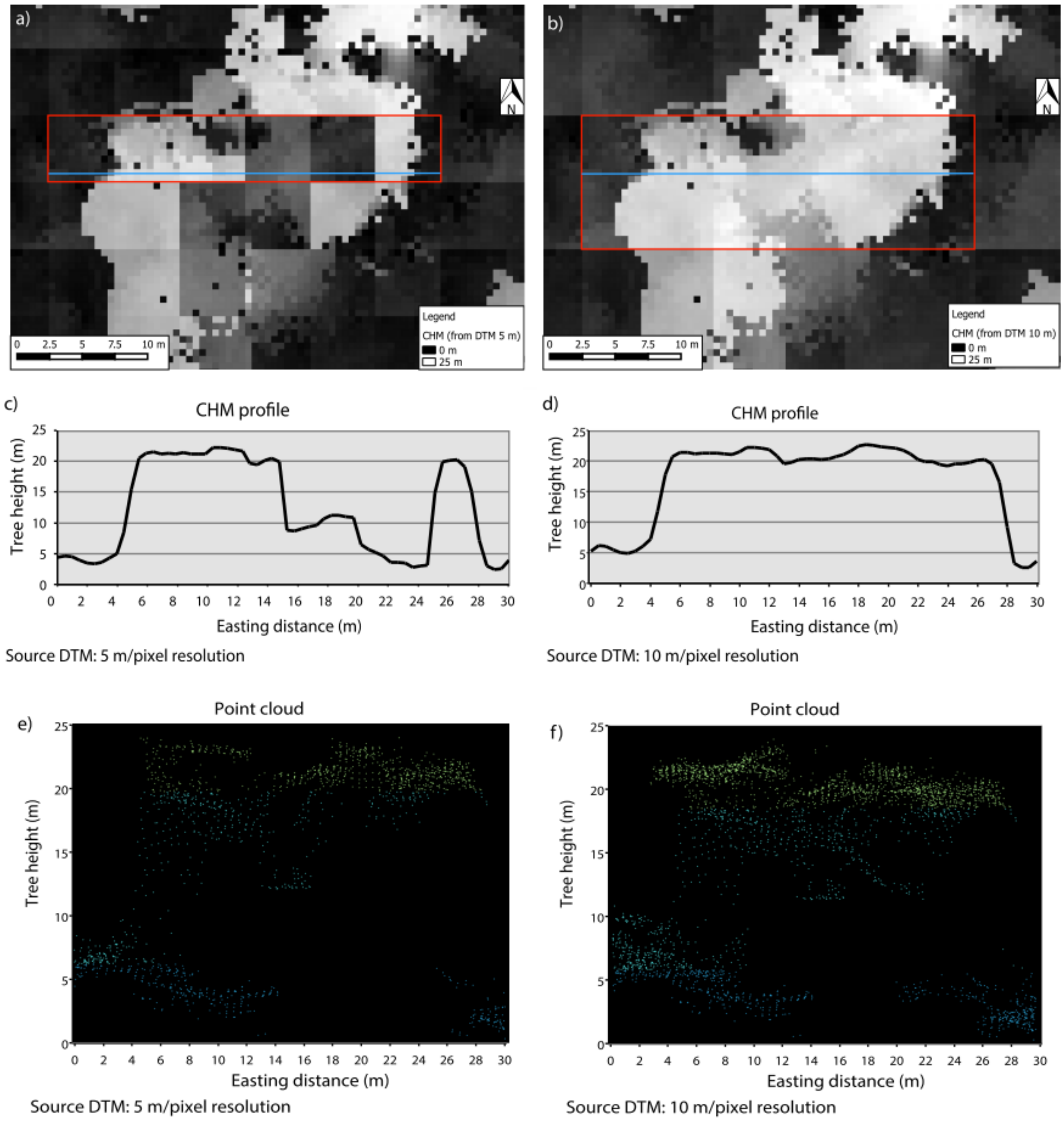


*Figure 15: Canopy height model with 0.5 m/pixel resolution, calculated from DTM with 5 m/pixel resolution (CHM5; **a)** and from DTM with 10 m/pixel resolution (CHM10; **b**). Blue lines (**a**, **b**) show the transects for which CHM profiles are shown in **c** and **d**, respectively. Red rectangles (**a** and **b**) marked the areas for which the point cloud profile is shown in **e** and **f**, respectively. The increment of the spacing from 5 m to 10 m for the calculation of DTM allows the selection of low points (more probably related to terrain) from the open areas, reducing the obstruction caused by dense canopy cover.*

5.1.3 *Adjusted canopy cover index*

In order to complete the corresponding estimation of canopy cover (CC) of vegetation higher than five meters, only the CHM10 was used. However, in several cases, relatively big patches of live forest with dense CC also produced errors on the calculations of CHM10, as discussed for CHM5. Abrupt changes of tree height on CHM were always cross-checked on the corresponding orthomosaic. When an error was confirmed, the closest well-predicted tree height was assigned to the point being analysed. For every plot, all of the points in the sampling grid created for estimations of partial CC were analysed to extract the tree height class (THC) of the corresponding point. Percentage frequency of points per THC (THC1, THC2, THC3, and lower than 5 m) were calculated for the 70 ground plots, and correlated to basal area (BA).

5.1.3.1 Multiple linear regression

The outputs of the multiple linear regression to estimate BA by the independent variables THC1, THC2, and THC3 are shown in Table 9, and the model for the prediction of BA is presented following. This model has an adjusted r^2 of 0.76, and all of the independent variables are significant at more than 99 % of confidence.

*Table 9: Multiple linear regression analysis outputs related to the model shown in Formula 2. *** means that the inclusion of the independent variables is significant at a higher confidence than 99 %.* ***a****,* ***b****, and* ***c*** *are in reference to the coefficients assigned to the independent variables.*

Variable	Coefficient	Standard deviation	t-value	p-value	
Intercept	-0.93010	0.86051	-1.081	0.284	
THC1	0.14742 (a)	0.02998	4.918	6.26 x 10-6	***
THC2	0.22734 (b)	0.01810	12.560	<2 x 10-16	***
THC3	0.32320 (c)	0.06330	5.106	3.09 x 10-6	***

The prediction of BA from partial CC at the THCs is as follows: *BA = 0.14742 × THC1 + 0.22734 × THC2 + 0.32320 × THC3 - 0.93010*. From this formula, *Ratio1 (a/b) = 0.648* and *Ratio2 (c/b) = 1.422* could be calculated. Ratio1 expresses that CC related to trees of THC1 have 35.2 % less impact on the BA than those from THC2. Ratio2 expresses a 42.2 % stronger impact of THC3 on BA in comparison with those of THC2. That is probably due to the diameter at breast height (DBH) of the trees, which is expected to be smaller when the trees are shorter. The adjusted canopy cover index (ACCI) was calculated for the 90 plots (70 ground inventory plots and 20 image plots) by Formula 20.

$$\text{ACCI} = 0.648 \times \text{THC1} + \text{THC2} + 1.422 \times \text{THC3} \quad (20)$$

Where THC1, THC2, and THC3 are independent variables, the number *0.648* is the Ratio1 and the number *1.422* is the Ratio2.

To visualise the relation between ACCI and BA, data from the 70 plots, where ground inventory data and good quality CHM were available, were graphed. The scatter plot in Figure 16 shows the trend line of an adjusted polynomial regression of second order between the two variables. The dashed vertical lines in Figure 16 show the ACCI thresholds for defining fire-severity classes (VSB for 'very severely burned,' SB for 'severely burned,' 'burned,' and 'fully stocked').

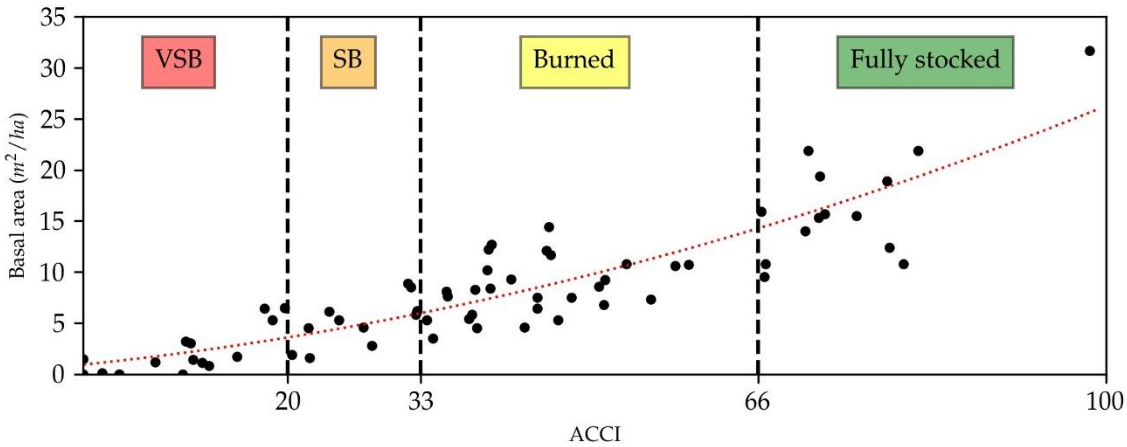


Figure 16: Scatter plot of ACCI values and basal area for each of the 70 plots, where both data were available (black dots). The plot shows the thresholds (black dashed line) for defining strata of fire-severity based on ACCI values (VSB for 'very severely burned,' SB for 'severely burned,' 'burned,' and 'fully stocked'). The red dotted line shows the trend line of an adjusted polynomial equation of second order.

5.1.4 Image classification

Based on the applied segmentation, 12,991 polygons of an average size of 3,036 m² from a total area of 3,944 ha were obtained. Figure 17 and Figure 18 show the resulting maps from both classifications of the segmented SPOT6 image, BA-based and ACCI-based, respectively.

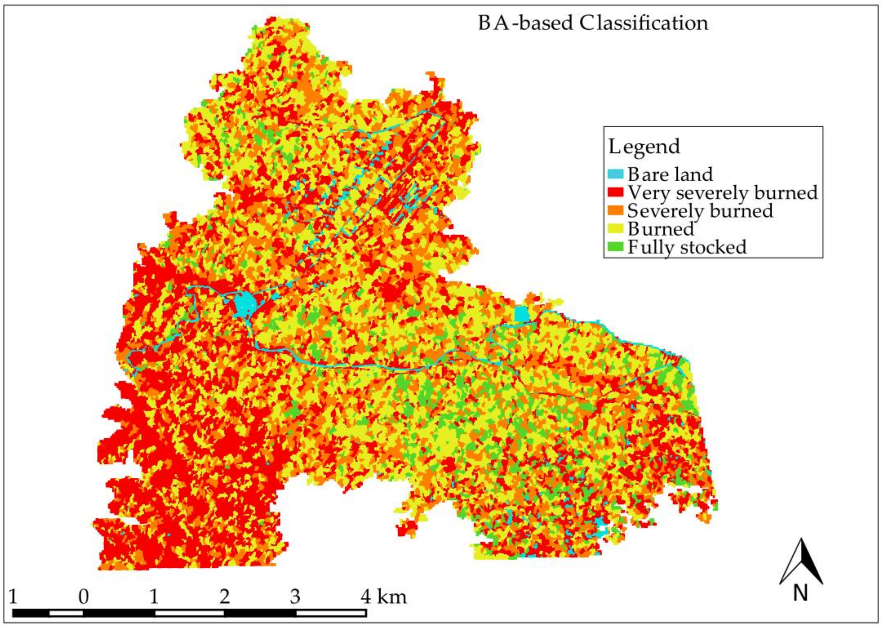


Figure 17: Maps of the SPOT6 image classification trained out of BA data from ground inventory.

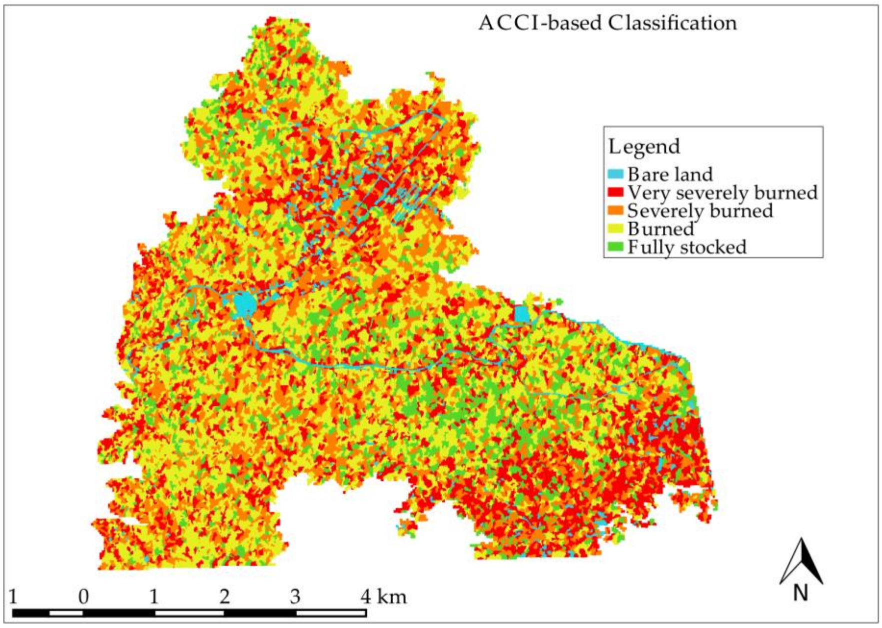


Figure 18: Maps of the SPOT6 image classification trained out of ACCI from UAV image analysis.

The matrices used for the calculations of the Cohen's Kappa coefficient (k) are reported on Table 10. The overall accuracies of the classification show no statistically significant differences (p-value: 0.43): *k* of 0.60 (69.7 % of the plots correctly predicted, SE: 0.04) on the BA-based classification, and *k* of 0.55 (67.1 % of the plots correctly predicted, SE: 0.04) on the ACCI-based classification.

Table 10: Matrices of predicted and actual strata used for the calculations of the Cohen's kappa coefficient of both classifications (the ACCI-based and the BA-based classifications). SB is the abbreviation used for the stratum 'severely burned,' and VSB of the stratum 'very severely burned.'

		Actual stratum									
		Fully stocked		**Burned**		**SB**		**VSB**		**Total**	
		ACCI	BA	**ACCI**	BA	**ACCI**	BA	**ACCI**	BA	**ACCI**	BA
Predicted stratum	**Fully stocked**	**12**	6	**3**	0	**0**	0	**0**	1	**15**	7
	Burned	**5**	7	**18**	24	**6**	2	**2**	1	**31**	34
	SB	**0**	1	**6**	2	**6**	9	**3**	4	**15**	16
	VSB	**0**	3	**0**	1	**0**	1	**15**	4	**15**	9
	Total	**17**	17	**27**	27	**12**	12	**20**	20	**76**	76

Table 11 compares the results of the classification of the segmented SPOT6 scene by both input thresholds BA-based and ACCI-based, with the classes 'severely burned' and 'VSB' aggregated in one class, representing the least stocked third following the ACCI gradient of all strata. For all the strata, the relative estimation error of ACCI-based classification is lower. In this classification, for the strata 'burned' and 'fully stocked,' the error is lower than the target of 20 % (as it is prescribed for inventories in Argentina). However, the most damaged third ('very severely burned' and 'severely burned') presents a stratified relative estimation error over the limit of 20 % in both classifications. Since the calculations of relative error are based on average BA of the stratum (Formula 7; section 4.2.6.2 'Comparison of BA-based and ACCI-based classifications'), the estimation errors of low average BA strata are difficult to reduce (Sokal & Rohlf 1997).

Table 11: Description of the strata based on basal area (BA; m²/ha). BA-based classification and ACCI-based classification are compared by metrics and errors. Strata 'very severely burned' (VSB) and 'severely burned' (SB) are reported together.

Strata	Variable	BA-based classification	ACCI-based classification
VSB + SB	Area (ha)	2191.0	1850.1
	Number of plots	35	30
	Average BA (m^2/ha)	4.3	3.2
	Max BA (m^2/ha)	14.4	8.9
	Min BA (m^2/ha)	0.0	0.0
	Estimation error (m^2/ha)	1.4	1.0
	Relative estimation error (%)	32.14	31.22
	Necessary plots to target error	90	73
Burned	Area (ha)	1369.4	1431.0
	Number of plots	34	31
	Average BA (m^2/ha)	10.0	8.4
	Max BA (m^2/ha)	31.7	14.4
	Min BA (m^2/ha)	3.1	3.1
	Estimation error (m^2/ha)	1.8	1.1
	Relative estimation error (%)	18.08	13.24
	Necessary plots to target error	28	14
Fully Stocked	Area (ha)	286.9	523.7
	Number of plots	7	15
	Average BA (m^2/ha)	15.7	16.4
	Max BA (m^2/ha)	21.9	31.7
	Min BA (m^2/ha)	3.0	9.5
	Estimation error (m^2/ha)	5.6	3.2
	Relative estimation error (%)	35.81	19.4
	Necessary plots to target error	23	15
Bare land	Area (ha)	96.4	139.4

The results of the most degraded third are then shown separately for the strata 'very severely burned' and 'severely burned' (Table 12). This separation was necessary for two reasons: (1) to reduce the influence of the zero values of BA in the class by having two more homogeneous strata, and (2) to identify and isolate those stands with an ACCI below 20 (closely related to CC), since a CC of 20% is a threshold for the definition of forest under Argentinian law.

Table 12: Description of the strata 'very severely burned' and 'severely burned,' based on basal area (BA; m²/ha). BA-based classification and ACCI-based classification are compared by metrics and errors.

Strata	Variable	BA-based classification	ACCI-based classification
Very severely burned	Area (ha)	1237.6	858.0
	Number of plots	19	15
	Average BA (m^2/ha)	3.7	1.04
	Max BA (m^2/ha)	14.4	3.2
	Min BA (m^2/ha)	0.0	0.0
	Estimation error (m^2/ha)	2.25	0.59
	Relative estimation error (%)	60.5	57.03
	Necessary plots to target error	174	121
Severely burned	Area (ha)	953.4	992.1
	Number of plots	16	15
	Average BA (m^2/ha)	5.0	5.4
	Max BA (m^2/ha)	14.0	8.9
	Min BA (m^2/ha)	0.8	1.9
	Estimation error (m^2/ha)	1.7	1.07
	Relative estimation error (%)	32.	19.85
	Necessary plots to target error	44	15

The amount of area assigned to each of the strata are similar in both classifications, except an inverse difference of around 300 ha between the most and the least stocked strata (Table 11). On the BA-based classification, 2,191 ha are assigned to the least stocked third, which corresponds to 1,237.6 ha of the stratum 'very severely burned' and 953.4 of 'severely burned' (Table 12). On the most degraded third, only slight differences were reported between the classifications in terms of areas classified as 'severely burned.' However, a great difference can be identified on the stratum 'very severely burned.' That can be explained with the results reported in Table 10, which show that out of nine plots predicted as 'very severely burned' on the BA-based classification, three were actually 'fully stocked.'

The stratum 'very severely burned' has low stocks, leaving open areas for colonisation by grass and vines (Arturi et al. 2006; Balducci et al. 2012). Therefore, this abundance of green vegetation, might cause that the stratum 'very severely burned' display similar spectral characteristics to the stratum 'fully stocked' (Sai & Mikhailov 2017). In the ACCI-based classification, since it also includes information from CC, a reduction of the areas misclassified due to similar spectral responses of grass (and vines) as 'fully stocked' forest could be achieved. From the ACCI-based classification, homogeneous strata with a reduced number of outliers, and a relative estimation error lower than 20 %, was achieved for all the areas with an ACCI value higher than 20.

Table 11 and Table 12 also report the number of necessary ground plots to achieve the target error. For the BA-based classification, 28 and 17 additional ground plots would be necessary in order to achieve the target error for the classes 'severely burned' and 'fully stocked,' respectively, whereas no additional plots are necessary for the ACCI-based classification.

Statistically significant differences can be identified between all the strata from the ACCI-based classification. On the BA-based classification, only between the two middle strata ('burned' and 'severely burned') significant differences exist. (Figure 19). The better precision of the ACCI-based classification, in comparison with the BA-based classification, might be due to a bigger number of training areas used for the ACCI-based classification (44 ground plots and 20 image plots, compared to only 47 ground plots). The reduction of the stratified estimation errors was also achieved by the inclusion of structure parameters, and not only spectral response, which support reducing the number of outliers in the ACCI-based classification. This is one of the main outputs of this research because, having used the same number of ground plots, more homogeneous strata were achieved by additional samples on UAV imagery for which ACCI values were calculated.

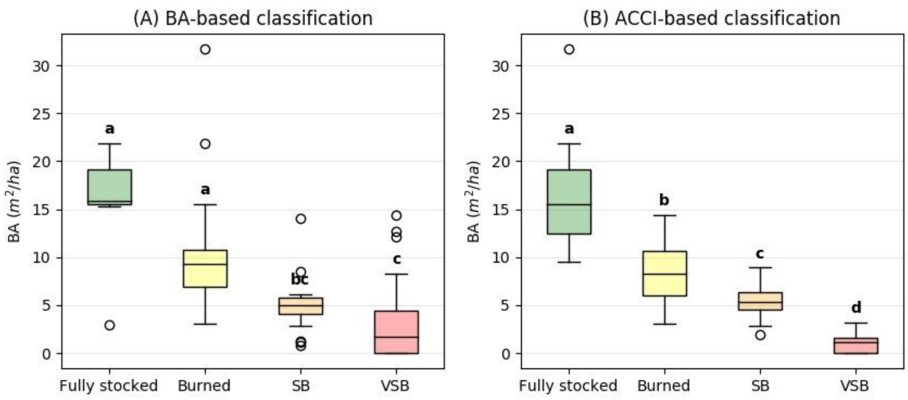


*Figure 19: Box plot of basal area (BA) by forest stratum reported separately for the results of the BA-classification **(A)** and the ACCI-based classification **(B)**. Different letters report statistically significant differences between the mean BA among the strata, and white circles report outliers.*

5.1.5 Validation of CHMs

After achieving an acceptable relative estimation error for the degradation strata, the 90 reference trees were grouped by fire-severity strata. Only 71 out of the 90 reference trees measured during the inventory were satisfactorily analysed, because dead trees were excluded from this part of the analysis. This exclusion was completed after noticing a great error on those cases, probably due to an extremely low canopy size and density. Only 13 live trees were analysed on the third most degraded group of strata, due to the high number of dead trees in this group. Therefore, this group was not subdivided further for this part of the analysis. However, three groups of forest degradation were considered: (1) 'fully stocked,' (2) 'burned,' and (3) 'severely burned' (SB) together with 'very severely burned' (VSB). Coefficient of determination (r^2), root mean square error (RMSE), and mean absolute error (MAE) are shown in Table 13.

Graphs of correlations are shown in Figure 20 by strata and by CHMs: (1) CHM5: CHM calculated from DTM with 5 m/pixel of resolution, and (2) CHM10: CHM calculated from DTM with 10 m/pixel of resolution. For all the analysed strata, tree height is underestimated. This might be due to the technical limitations of optical sensors to reach data under the canopy, and low vegetation. The more degraded the forest, the lower the obstruction caused by forest canopy, and consequently, the lower the errors. This tendency towards the reduction of estimation errors on more degraded strata occurs in both CHMs.

Table 13: MAE of tree height estimation by CHM5 and CHM10, RMSE, and coefficient of determination (from the correlation of observed and estimated tree height) discriminated by level of degradation.

Group	Variable	CHM5	CHM10
Fully stocked	Mean absolute error (m)	6.784	4.535
	RMSE (m)	8.251	5.494
	r^2 to observation measurements	0.0567	0.1232
Burned	Mean absolute error (m)	4.019	3.388
	RMSE (m)	4.868	4.207
	r^2 to observation measurements	0.4353	0.4411
SB + VSB	Mean absolute error (m)	2.392	2.292
	RMSE (m)	2.963	2.849
	r^2 to observation measurements	0.7939	0.795

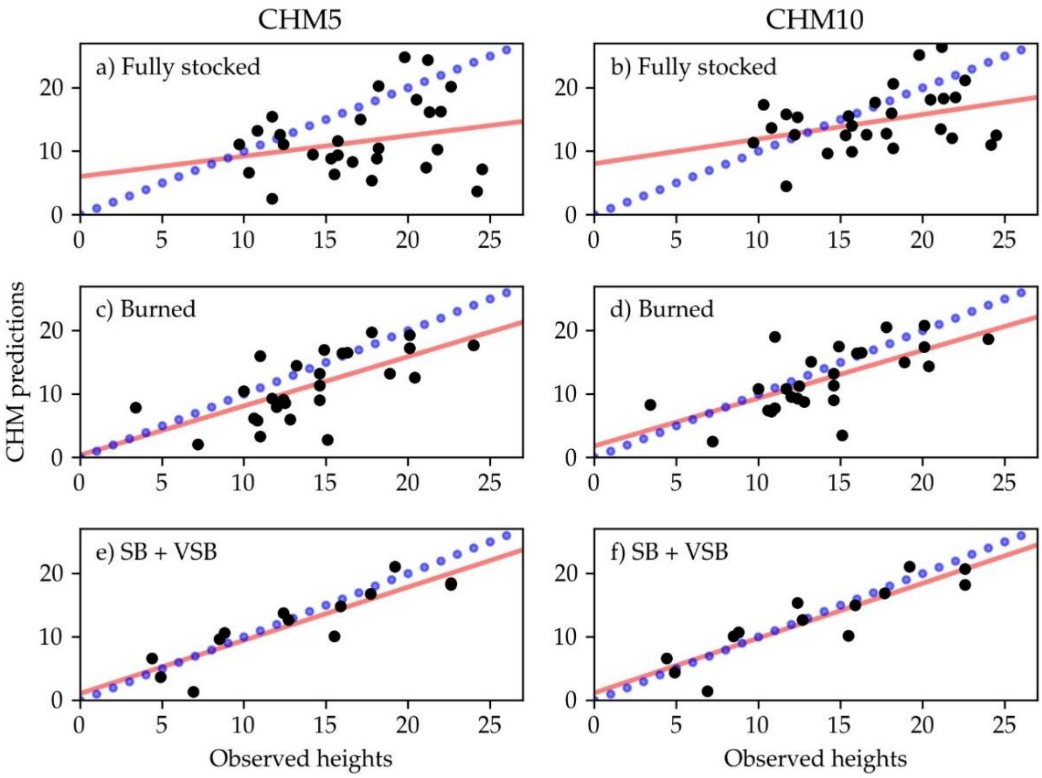


*Figure 20: Observed and predicted heights by CHM5 (**a**, **c**, **e**) and CHM10 (**b**, **d**, **f**) of the 71 reference trees (black dots), discriminated by level of degradation (**a** and **b** from stratum 'fully stocked;' **c** and **d** from stratum 'burned;' **e** and **f** from strata 'SB' and 'VSB'). Red lines are trend lines of the adjusted equation and the blue dotted lines are a reference line of the one-to-one ratio.*

5.2 Additional description of fire-severity strata

In the previous sections, the classification of degraded forests was conducted based on ACCI values, and relative estimation errors of the classifications, tested against BA, were shown. The results yielded a more precise classification when additional ACCI values from UAV imagery were used to train image classification, in comparison with the traditional area-based approach using only BA data from ground inventory. Consequently, homogeneous strata based on BA and forest structure parameters were created. However, in order to apply management, and possibly rehabilitation measures, a more detailed description of the forest stock is desirable. In this section, the strata acquired from ACCI-based image classification are described based on ground inventory data. Because of the operational perspective of this dissertation, species are not considered individually, but in groups of species based on their timber value. Eliano et al. (2009) classified tree species in Yungas into three groups based on their timber value: 'most wanted,' 'wanted,' and 'indifferent' species (details, see 4.2.7, Table 5). In the rest of this chapter, this classification is used to describe the strata.

Figure 21 shows a boxplot of BA per stratum. Mean difference by Welch t-test analysis, displayed with different letters on top of the boxes' caps, show that the mean BA is different among the strata (Williamson, 2008). The means of BA are statistically different across the strata.

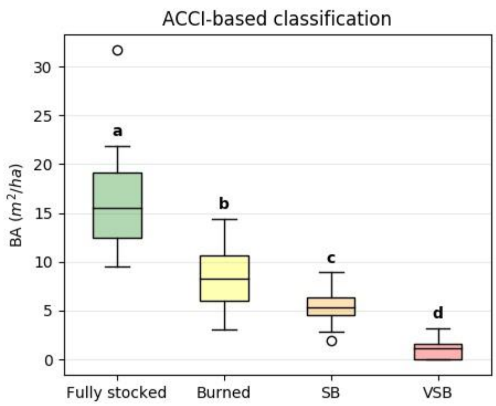


Figure 21: Boxplot of BA for each of the stratum obtained by the ACCI-based classification. Welch t-test was used to assess statistical differences in the mean BA across the strata. Different letters show statistically significant differences with a confidence of 95 %.

The DBH-distribution of the trees in the different strata was analysed in order to describe the present and future potential use of the forest (Figure 22 [Balducci 2012]). Considering all the tree species present in the forest, the diametric distribution of the stratum 'fully stocked' shows the reverse J-shape typical for uneven-aged natural forest (Lamprecht 1990). A high number of small trees is present, and their stocking density (number of trees/ha) is progressively decreasing with the increasing diameter of the trees. The strata 'burned,' 'severely burned,' and 'very severely burned' (VSB) have also responded to the same reverse J-shape but, as expected, with a lower number of trees. It is expected that the mortality due to fire increases with increasing fire-severity and decreasing DBH (Dunn 2015), although this tendency might be weaker or stronger depending on the sensitivity of the species to fire. This gradient is illustrated in Figure 22, for the respective diameter classes. The stocking densities between the DBH-classes 20-30 cm and 40-50 cm in the stratum 'fully stocked' is reduced by 72 % (from 82 trees/ha to 23 trees/ha), whereas in the strata 'severely burned' and 'very severely burned' the density is kept almost constant among those DBH-classes. In other words, the effect of fire on tree mortality is reduced when increasing the DBH-class.

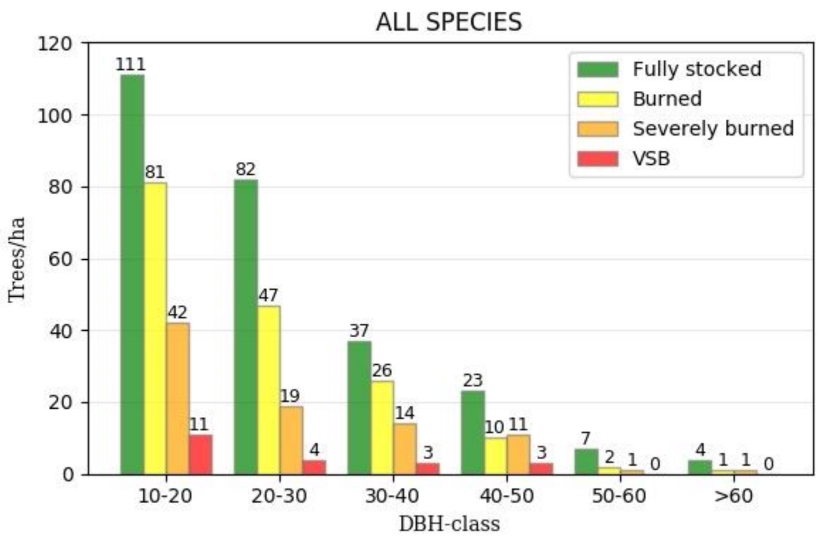


Figure 22: DBH-distribution of all species by degradation strata. Green is the stratum 'fully stocked;' yellow, 'burned;' orange, 'severely burned;' red, 'VSB.'

To evaluate the potential for future use of the forest, more information about the species composition is needed. Unfortunately, to-date, species cannot be reliably identified by remote sensing (RS) in a large scale. This is especially difficult when the forest is diverse and composed of broadleaf species (Baldeck et al. 2015), which is the case of the Yungas cloud Forest. However, having delineated and defined degradation levels caused by mixed-severity fires, it is expected that the final composition of the forest is influenced by the fire-severity.

Comparing the illustration of stocking density of all tree species (Figure 22) with the sum of 'most wanted' and 'wanted' species (Figure 23), it can be appreciated that approximately 40 % of the small trees, which are supposed to be young, in the 'fully stocked' forest belong to the tree group 'indifferent.' When all species are considered (Figure 22), the difference of density between the stratum 'fully stocked' and the stratum 'burned' are 24 % for the DBH-class 10-20 cm and 43 % for the DBH-class 20-30 cm. In Figure 23, where only the diameter distribution of the 'most wanted' and 'wanted' species are reported, those changes represent 0 % for the first and 24 % for the second DBH-class. From those differences, it can be observed that, 'indifferent' species show a greater sensitivity to low fire-severity than the 'most wanted' and 'wanted' species. However, it is not surprising, since 'wanted' and 'most wanted' species have mainly denser wood and thicker bark (for instance 'cebil moro,' and 'urundel,' in comparison with 'laurel negro'), and are therefore more fire-tolerant.

Figure 23B and Figure 23C show the diametric distribution of the 'most wanted' and 'wanted' species, respectively. It can be appreciated that mainly the stratum 'fully stocked' has a greater density for the 'most wanted' species than for 'wanted' species.

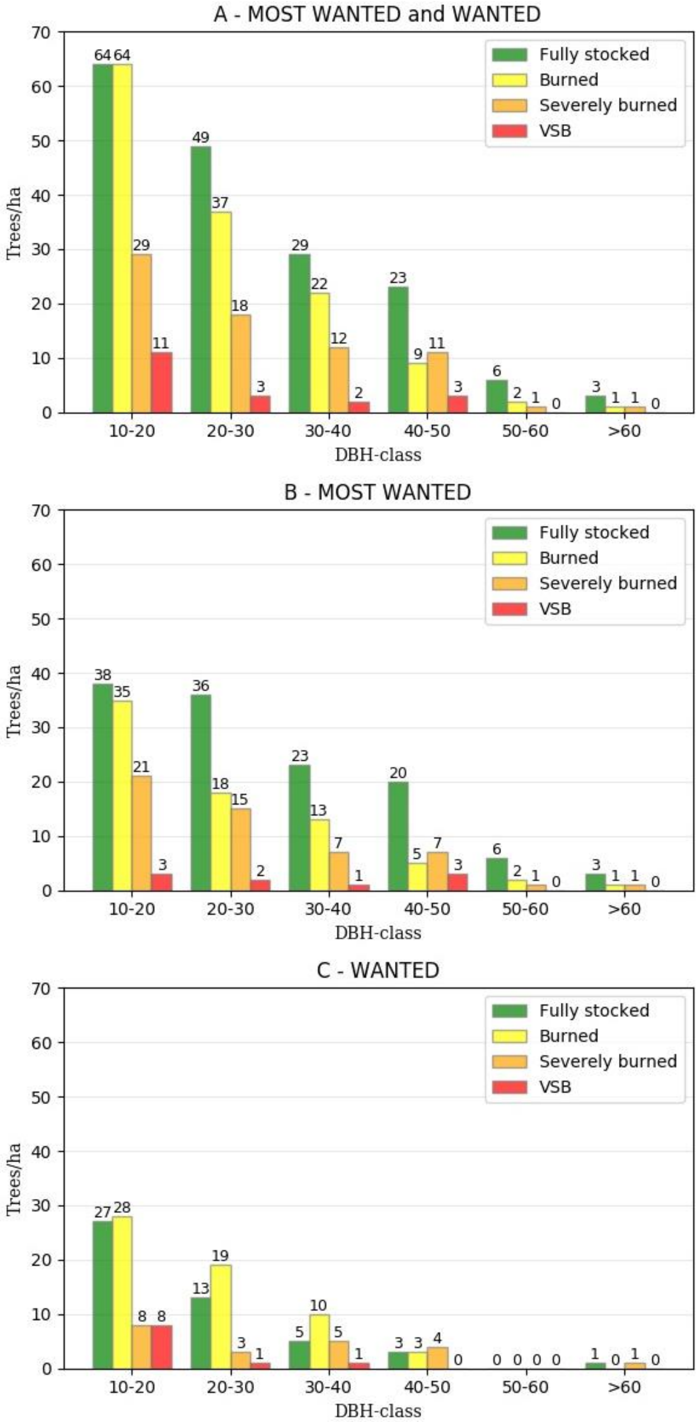


*Figure 23: Diametric distribution of the 'most wanted' and 'wanted' species (**A**), only 'most wanted'* ***(B),*** *and only 'wanted' species (**C**). On every figure, this information is also shown by degradation strata. Green is the stratum 'fully stocked;' yellow, 'burned;' orange, 'severely burned;' red, 'VSB.'*

Based on the diameter distribution of the 'fully stocked' and 'burned' strata, in principle, a forest management of the existing stand seems to be feasible, since the density of ´most wanted' and 'wanted' species are distributed in a reverse J-shape, and with a considerably high number of trees per hectare (174 trees/ha). However, the DBH-distribution of the existing trees is not enough to decide on the potential utilisation of the forest, since the health, shape, and spatial distribution of the trees will define whether they are, or are not, future crop trees (FCT) or mature trees (Brassiolo et al. 2013). Figure 24A shows the DBH-distribution of the silvicultural classes FCT. FCTs are healthy trees of 'wanted' and 'most wanted' species, which were also not severely damaged by fire. Furthermore, those trees must be evaluated locally on their shape and spatial distribution. For example, a well-formed tree of a 'wanted' species can be considered a competitor of a well-formed tree of one of the 'most wanted' species, but if the tree from the 'most wanted' species has an undesired shape (or it is rotten), this one would be a competitor of the tree of a lower class.

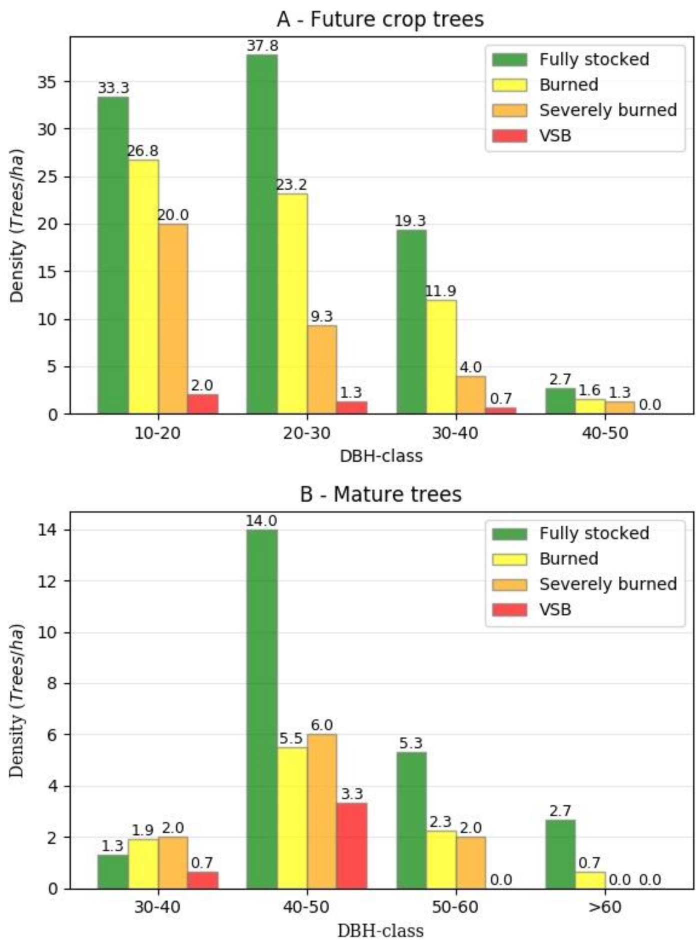


*Figure 24: DBH-distribution of the density of the silvicultural classes 'FCT' (**A**) and 'matures trees' (**B**). On every figure, this information is also shown by degradation strata. Green is the stratum 'fully stocked;' yellow, 'burned;' orange, 'severely burned;' red, 'VSB.'*

Figure 24B reports the DBH-distribution of mature trees. Mature trees are trees of 'wanted' or 'most wanted' species which comply with the minimum diameter for logging required by decree N° 15,142/60 (1960, Annex 1). Furthermore, those trees do not show any external sign of wood putrefaction or decay, and have a desirable shape for timber use. Based on the guidelines for the management of the native forest in the Yungas (Balducci et al. 2012; Grulke et al. 2013), the minimum number of FCTs and mature trees to assure the actual management and future stock in the forest are 100 and 10, respectively. Based on Table 14, all strata lack future crop trees, but only the stratum 'very severely burned' lacks mature trees.

Tree density, DBH-distribution, and stocking volume of mature trees per hectare are reported separately for `most wanted' and `wanted' species in Figure 25 and Figure 26.

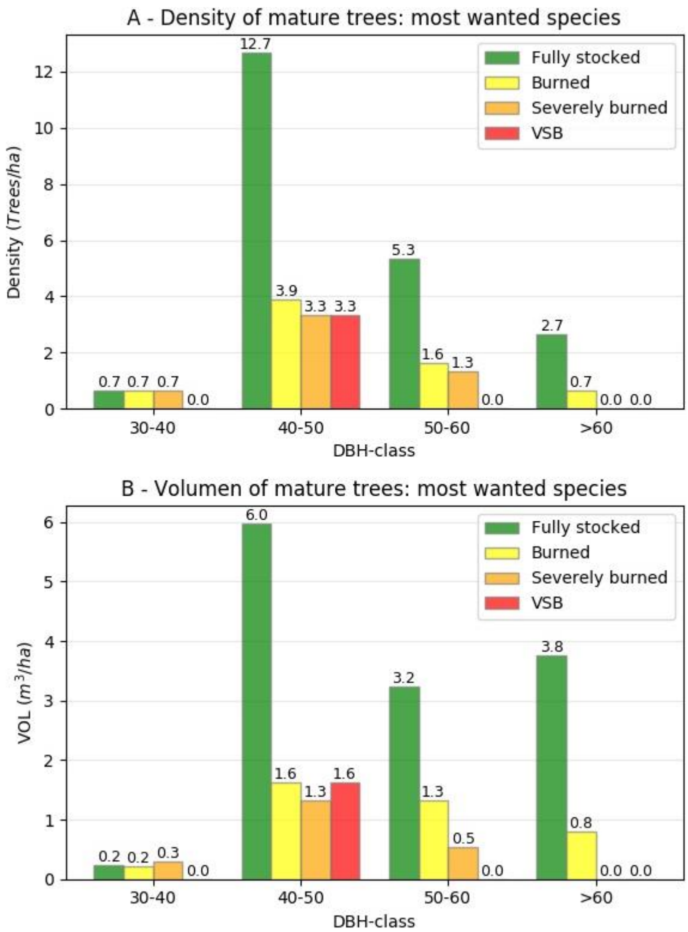


*Figure 25: DBH-distribution of the density (**A**) and volume (**B**) of the 'most wanted' species. On every figure, this information is also shown by degradation strata. Green is the stratum 'fully stocked;' yellow, 'burned;' orange, 'severely burned;' red, 'VSB.'*

The volume of timber from mature trees shows the potential revenue if the forest is harvested. Figure 25 shows a higher number of trees per hectare, and consequently a higher volume of timber in the strata 'fully stocked' in comparison with the other strata. This difference between strata is not present for the 'wanted' species (Figure 26), for which the DBH-distribution, and consequently volume of timber per hectare, are pretty much random among the strata, or respond to other factors not analysed in this dissertation. In both cases, in the stratum VSB, the stock of existent mature trees is scarce.

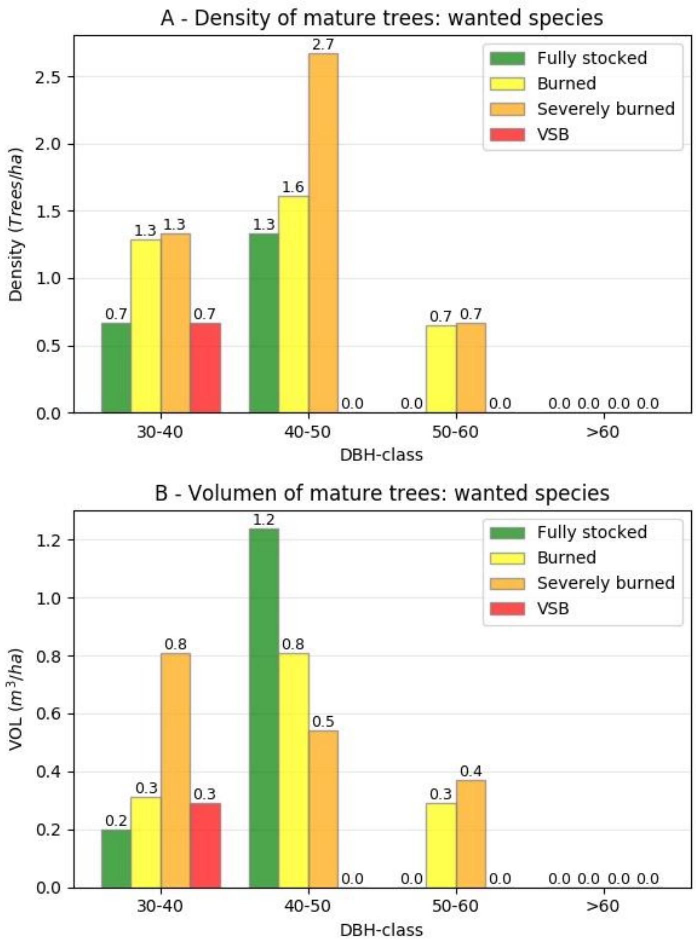


*Figure 26: DBH-distribution of the density (**A**) and volume (**B**) of the wanted species. On every figure this information is also shown by degradation strata. Green is the stratum 'fully stocke;' yellow, 'burned;' orange, 'severely burned;' red, 'VSB.'*

Mean density of total live trees, FCT, and mature trees were tested with a Welch t-test in order to prove significance across the strata. For all the cases, except for the density of 'mature trees' between the strata 'severely burned' and 'burned,' statistically significant differences were found.

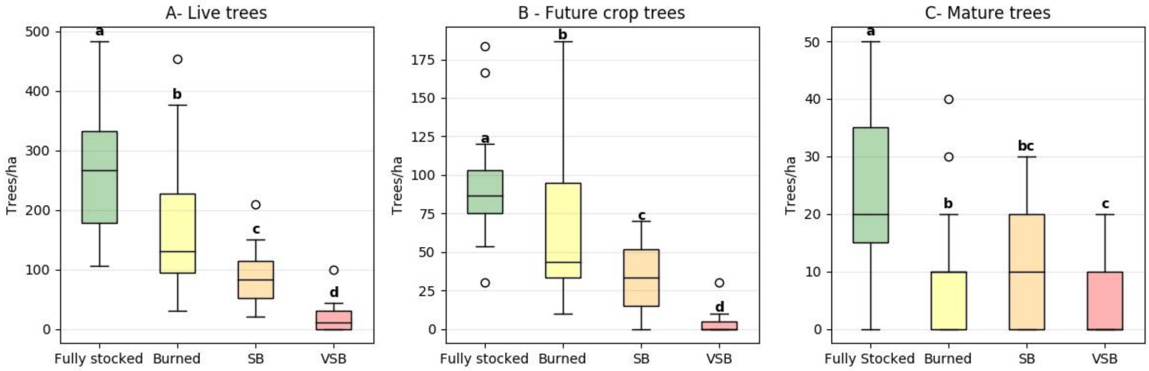


Figure 27: boxplot of densities of all live trees, FCTs, and mature trees across the strata. Welch t-test was used to assess statistical difference in the mean density across the strata. Different letters show statistically significant differences with a confidence of 95 %.

Finally, regeneration (seedlings and saplings) density is reported in Figure 28. Regeneration trees were those higher than 50 cm, and with DBH lower than 10 cm. The data was processed considering that only trees higher than 2 m would survive damage caused by animals, and therefore are considered as 'established regeneration' (Brassiolo et al. 2013). In general terms, for seedlings shorter than 2 m, the density of regeneration trees is lower with increasing degree of degradation, and vice versa for trees taller than 2 m. This can be explained by the favourable competition conditions after the fire, producing a boom of regeneration when seeds are released, although this favourable condition is later limited by the competition for sunlight and water by upcoming vines and shrubs. In the case of 'fully stocked' forest, smaller seedlings are present due to a higher density of seed-trees, which also limit their survival. Consequently, between 90 and 100 % of those seedlings die probably due to competition for resources with older trees or understory vegetation, or to wildlife browsing (Carter & Fredericksen 2007).

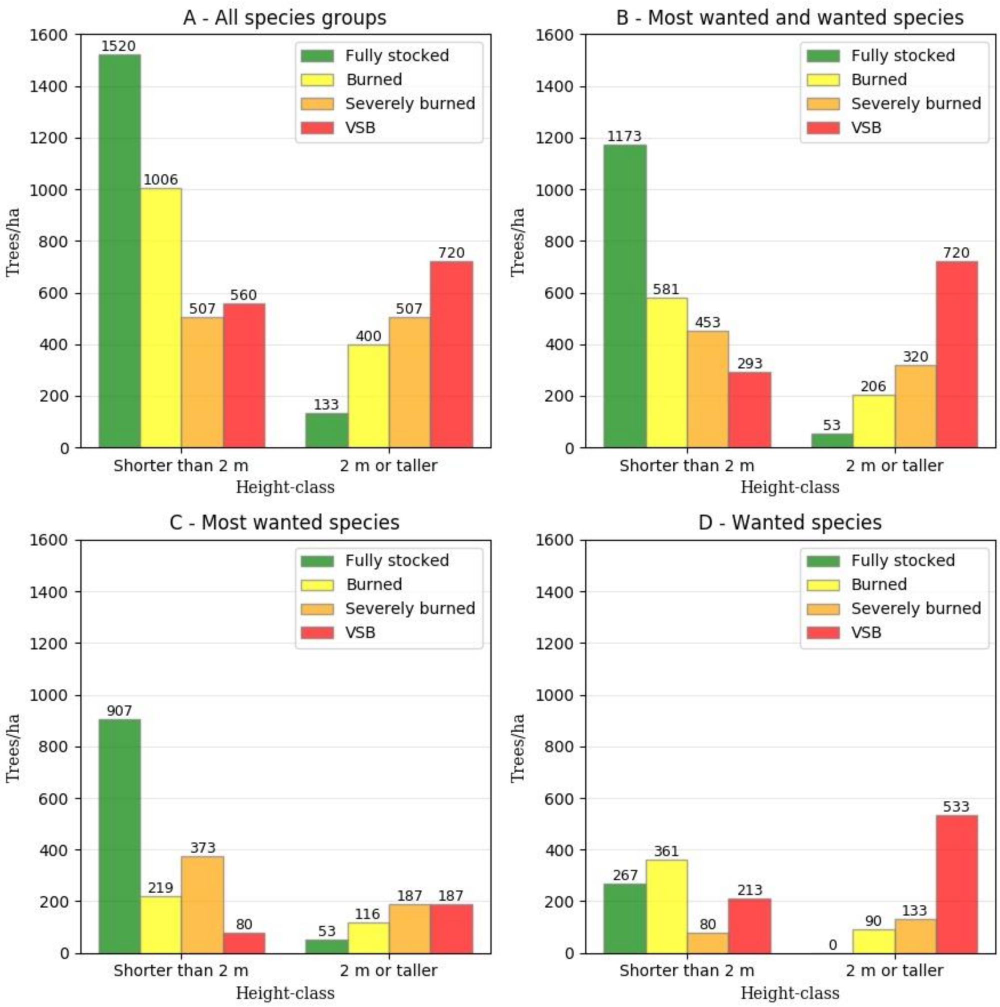


*Figure 28: Regeneration density reported by species group among strata: all species (**A**), the sum of 'most wanted' and 'wanted' species (**B**), only 'most wanted' species (**C**), and only 'wanted species' (**D**). Green is the stratum 'fully stocked;' yellow, 'burned;' orange, 'severely burned;' red, 'VSB.' Regeneration is reported in two height classes: shorter than 2 m and equal to or taller than 2 m.*

The species 'most wanted' and 'wanted' represent close to 50 % of the trees shorter than 2 m, and 100 % of the trees taller than 2 m in the stratum 'very severely burned.' However, the number of 'established regeneration' (seedlings higher than 2 m) is, for all the strata, lower than the desirable of 833 trees/ha, which would be the density of planted trees in a conventional plantation with planting spacing of 4 m x 3 m. Therefore 833/ha could be considered a benchmark to assure the future development and use of the forest, if the spatial distribution is homogeneous among the area. The insufficient regeneration indicates the need for rehabilitation measures.

Table 14 shows an overview of the average values from the previously mentioned variables of interest: area, BA, density of live trees, FCTs, and mature trees, volume of mature trees, and regeneration. Despite ACCI thresholds being used to define the stratification of the forest into four fire-severity damage strata, those other variables are used to support decision makers to decide about the need for restocking the forest by enrichment planting, management of regeneration, or liberation thinning.

5.3 Establishing forest management units

The tool Hot Spot Spatial Analysis (Gi-Ord Gi*) available on the software ArcGIS 10.3 was used to identify areas where high and low values of ACCI were aggregated. A multi-scale analysis was applied in order to compare the results of clustering for four scenarios, analysing clusterisation at neighbouring areas of 10, 20, 30, and 40 ha, resulting in threshold radii of 178, 252, 309, and 357 m, respectively. Considering an average of 3,129 m^2 per feature, 32, 64, 96, and 128 features have taken part in the analysis. The number of involved features is, for all the cases, higher than the minimum of eight neighbouring features necessary for Gi* analysis to keep normality (Nelson, 2008).

The result of the analysis is a map of hot and coldspots for each scenario. The resulting coldspot areas are clusters with significant aggregation of features of low values of ACCI. In hotspot areas, features of high values of ACCI are aggregated. Finally, a third group corresponds to all the areas where no statistically significant aggregation of features of high or low values of ACCI could be identified. In this group, the distribution of fire damage responds to a random arrangement.

Table 14: Results of the forest inventory by strata. Results are reported by mean values per strata, based on the ACCI-based classification. MT refers to 'mature trees.'

Strata	Area (ha)	Basal area (m^2/ha)	Future crop trees (n°/ha)	Mature trees (n°/ha)	Live trees (n°/ha)	Volume of MT of most wanted species m^3/ha (n°/ha)	Volume of MT of wanted species m^3/ha (n°/ha)	Regeneration < 2 m (n°/ha)- most wanted and wanted	Regeneration > 2 m (n°/ha)- most wanted and wanted
Very severely burned	858.0	1.0	4	4	20	1.63 (3)	0.29 (1)	293	720
Severely burned	992.1	5.4	35	10	88	2.15 (5)	1.71 (5)	453	320
Burned	1431.0	8.4	65	10	167	3.96 (7)	1.40 (3)	581	206
Fully stocked	523.7	16.4	93	23	264	13.20 (21)	1.44 (2)	1173	53
Bare land	139.4	----	----	----	----	----	----	----	----
Total	**3944.2**	**----**	**----**	**----**	**----**	**----**	**----**	**----**	**----**

5.3.1 *Moran's I Analysis*

To assess whether the spatial distribution of features is clustered, random, or disperse, a *Moran's I* analysis was run with 95 % of confidence prior to the cluster analysis for each of the four levels of neighbouring. Results are shown in Table 15. For all the cases, *Moran's I* index is positive, indicating that the data is clustered (positively autocorrelated). As the data set is the same at all scales, the expected *Moran's I* index is constant at the four scales. The variance is reduced when increasing the neighbouring area (therefore also the number of features analysed), since more features taking part in the analysis make the statistics more powerful. Therefore, the larger the area analysed, the larger the Z-score value, and stronger the rejection of the null hypothesis that the set of features is randomly distributed. For the four cases, the likelihood of not rejecting the null hypothesis is insignificant (p-value < 1×10^{-6}). In conclusion, the data are clustered at the four scales of analysis, and therefore the analysis to identify the clusters can be continued.

Table 15: Moran's Index, Expected Index, Variance, Z-score and p-value for each of the neighbouring scales for Moran's I analysis using the software ArcGIS 10.3. P-values report the likelihood of random distribution.

Scale of analysis	Moran's Index	Expected Index	Variance	Z-score	p-value	Null hypothesis
178 m	0.148	-8.1×10^{-5}	7×10^{-6}	56.105	$< 1 \times 10^{-6}$	rejected
252 m	0.133	-8.1×10^{-5}	4×10^{-6}	68.116	$< 1 \times 10^{-6}$	rejected
309 m	0.124	-8.1×10^{-5}	3×10^{-6}	76.134	$< 1 \times 10^{-6}$	rejected
357 m	0.118	-8.1×10^{-5}	2×10^{-6}	82.291	$< 1 \times 10^{-6}$	rejected

5.3.2 *Hot Spot Spatial Analysis (Getis-Ord Gi*)*

Hot Spot Spatial Analysis (Getis-Ord Gi*) was run to identify clusters of high and low values of ACCI. Since those cluster represent homogeneous areas in terms of ACCI values, they were later used to establish forest management units (FMUs). The resulting maps of the four distance threshold scenarios are compared in Figure 29, and thereafter they are separately shown for each of the scenarios: 178 m (Figure 30), 252 m

(Figure 33), 309 m (Figure 34) and 357 m (Figure 35). It can be observed, in accordance with Nelson & Boots (2008), that the larger the neighbouring scales, the larger the resulting clusters of hot and coldspots.

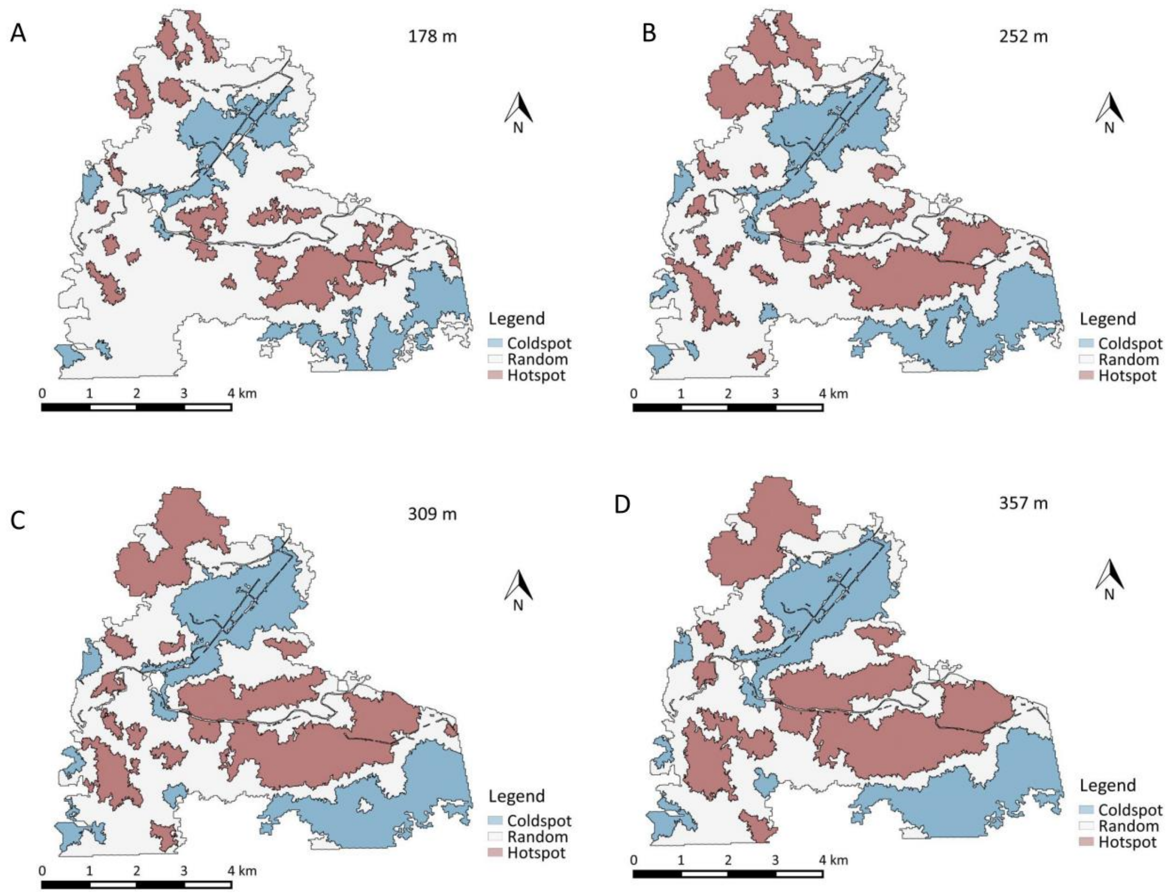


Figure 29: Hot Spot Analysis (Getis-Ord Gi) resulting maps at the four scales of analysis (**A**- 178 m, **B**- 252 m, **C**- 309 m, **D**- 357 m). Coldspots are coloured in blue, hotspots in red, and random areas in grey. The larger the scale of analysis, the fewer and larger are the resulting clusters.*

Every cluster is a result of the aggregation of many small features, which were assessed based on the median ACCI value of the stratum. This information is not lost, and the composition of every cluster was derived by overlaying the map of the clusters with the one of fire-severity strata. As examples, in this chapter two clusters (one hotspot and one coldspot) were analysed through the distance threshold gradient. Example clusters were selected with the constraint that they are not combined with other neighbouring clusters among the gradient. The cluster with the lowest weighted average ACCI value was selected as a coldspot example, and the one with the largest weighted average ACCI value as an example of hotspot for the first scale of analysis.

At the first scale of analysis (178 m radius), 15 clusters of coldspot (609.7 ha) and 20 of hotspot (579.3 ha) were identified (Table 16). The rest of the site (2676.6 ha) is composed of 9 areas where the distribution of ACCI values is random. Cluster 27 is the example chosen for coldspot (Figure 29, Figure 30, and Figure 31). At the first scale of analysis, it has an extension of 20.3 ha. It is composed of 0.1 ha of 'fully stocked' forest, 4.3 ha of 'burned' forest, 7.7 ha of 'severely burned' forest, 7.5 ha of 'very severely burned' forest and 0.6 ha of 'bare land;' accounting 0.7, 21.4, 38.1, 36.9, and 2.9 percent of the area occupied by 'fully stocked,' 'burned,' 'severely burned,' 'very severely burned,' and 'bare land,' respectively (Table 17).

Table 17 shows the weighted average of ACCI values which, for the given example is 24.9. Despite the composition of the cluster containing almost 40 % of 'very severely burned' forest and 'bare land' (median ACCI of 10 and 0), the overall cluster ACCI value is skewed to 24.9, and should be managed accordingly. In this context, it means that areas with a high ACCI value (well stocked) can be isolated to apply dedicate measures.

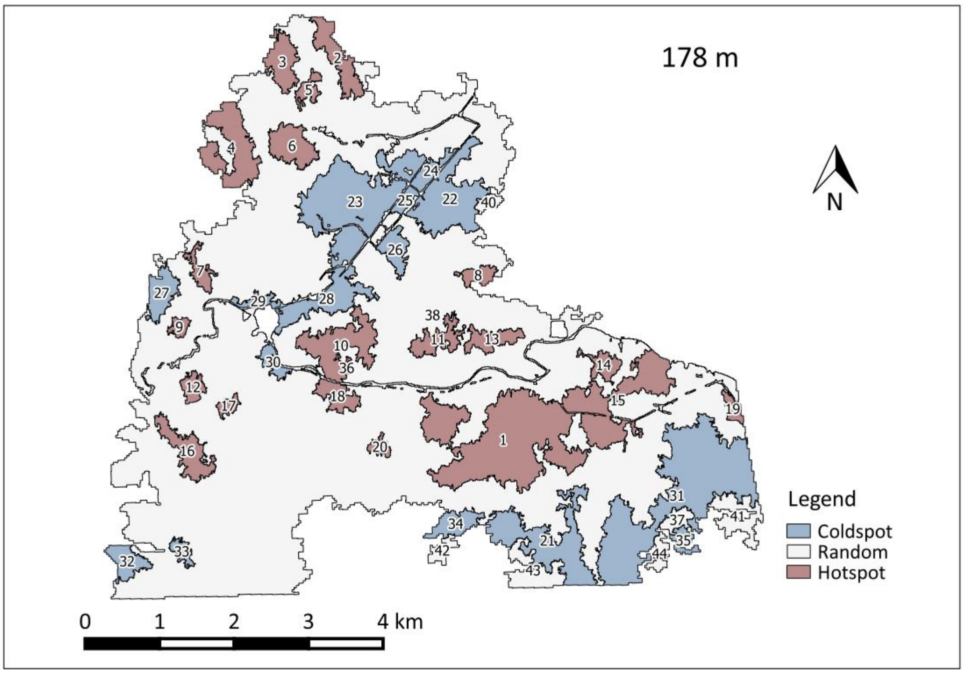


Figure 30: Hot Spot Analysis (Getis-Ord Gi) of ACCI values at a distance threshold of 178 m (10 ha). Red areas (hotspots) show clusters of high ACCI values, while blue areas (coldspots) show areas of features with low ACCI values. All features are larger than 5 ha, since smaller features were eliminated. Numbers show feature's ID.*

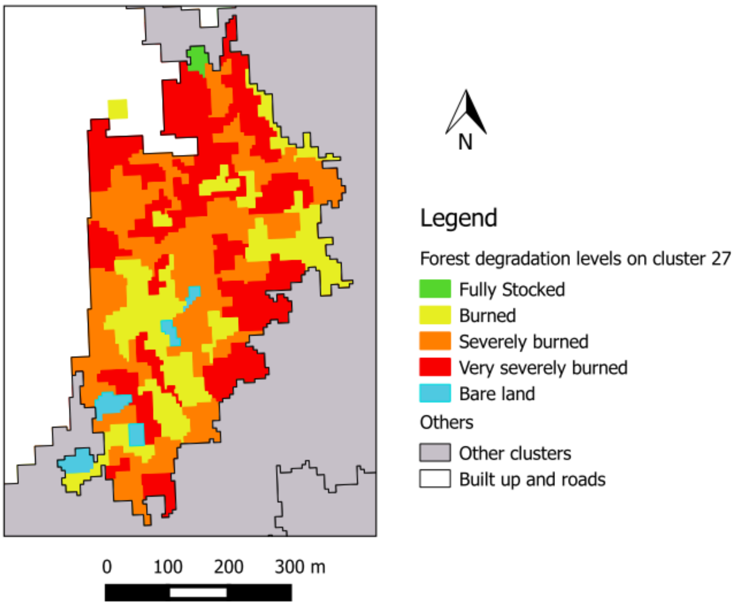


Figure 31: Composition of the cluster 27 from first scale of hotspot analysis (178 m). In the figure, it can be appreciated that this coldspot cluster is composed mainly of extremely degraded areas ('very severely burned' and 'severely burned' forest) and fewer areas of 'burned' and 'fully stocked' forests.

The selected cluster for the hotspot example is cluster 8 (Figure 29A, Figure 30, and Figure 32). This cluster is composed of high ACCI values on an area of 9.4 ha: 3.5 ha of 'fully stocked' forest, 4.9 ha of 'burned' forest, 0.9 ha of 'severely burned' forest, and none of 'very severely burned' and 'bare land' (Table 16), representing 37.9, 52.1, 10, 0, and 0 percent of the area occupied by 'fully stocked,' 'burned,' 'severely burned,' 'very severely burned,' and 'bare land,' respectively (Table 17). The weighted ACCI value of the cluster is 59.9, and it should be managed accordingly. In this context, it means that most of the area can be managed with standard measures (pruning, thinning, etc), while areas with low ACCI value (poorly stocked) can be isolated to apply a more intensive rehabilitation measure.

Table 16: Outcome table of clusters of hot and coldspot and random distribution of ACCI values at a threshold radius of 178 m. This table shows the area (ha) composition of forest (classified by fire-severity strata) of every cluster given by Hot Spot Analysis (Getis-Ord Gi). Shadowed cells highlight the cold (blue) and hot (red) spot examples.*

Clusters of ACCI values	Cluster ID	Fully stocked	Burned	Severely burned	Very severely burned	Bare land	Grand Total
Coldspot	31	11.3	21.4	45.6	97.3	12.4	188.0
	23	5.0	25.6	35.1	44.8	14.6	125.0
	21	7.9	7.6	17.8	37.3	3.5	74.1
	22	1.4	15.0	18.8	19.6	10.1	64.8
	28	0.1	9.7	15.9	10.4	3.6	39.7
	27	0.1	4.3	7.7	7.5	0.6	20.3
	34	1.0	3.9	2.6	8.8	0.6	16.9
	32	0.0	3.5	6.0	6.4	0.7	16.5
	26	0.0	3.3	3.7	8.5	0.3	15.8
	24	0.3	1.0	3.4	6.3	0.0	10.9
	30	0.0	0.6	5.5	2.9	0.0	9.0
	35	0.9	1.4	1.1	4.6	0.1	8.1
	29	0.0	1.8	3.4	1.8	0.3	7.3
	33	0.0	0.4	2.9	3.3	0.1	6.7
	25	0.0	0.0	0.9	5.6	0.0	6.5
Subtotal		**28.0**	**99.6**	**170.3**	**265.0**	**46.8**	**609.7**
Random	36	245.8	890.2	570.1	439.3	12.2	2157.6
	38	50.7	172.6	125.5	75.4	1.3	425.5
	43	5.5	3.8	9.0	7.8	0.8	26.9
	41	2.5	3.3	7.9	10.9	0.6	25.3
	39	2.9	4.9	1.9	1.4	0.0	11.2
	37	0.9	1.3	2.1	5.0	0.0	9.2
	44	2.0	2.5	1.8	1.6	0.0	7.9
	42	0.7	1.8	3.0	1.8	0.3	7.5
	40	0.3	3.6	0.7	0.9	0.1	5.5
Subtotal		**311.2**	**1084.0**	**722.0**	**544.1**	**15.2**	**2676.6**
Hotspot	1	71.8	63.5	23.3	20.2	0.1	179.0
	15	23.1	29.6	12.3	8.1	0.1	73.2
	10	16.1	23.5	8.2	1.9	0.0	49.7
	4	11.9	23.7	11.1	2.7	0.2	49.6
	2	7.2	13.5	5.3	1.7	0.0	27.7
	6	9.2	11.5	4.4	1.3	0.4	26.9
	16	6.8	14.2	3.8	1.9	0.2	26.8
	3	6.6	10.1	4.3	2.8	0.0	23.8
	11	4.3	8.4	5.5	1.0	0.0	19.2
	13	4.6	7.4	1.9	2.1	0.0	15.9
	18	4.5	8.7	1.7	0.8	0.0	15.7
	14	3.1	5.4	3.0	0.8	0.0	12.2
	7	1.7	4.6	3.9	0.2	0.0	10.4
	12	2.2	4.5	2.3	0.5	0.1	9.7
	8	3.5	4.9	0.9	0.0	0.0	9.4
	5	1.8	3.9	1.7	1.3	0.0	8.7
	19	2.4	0.3	2.6	0.2	0.0	5.5
	9	0.9	3.4	0.9	0.4	0.0	5.5
	20	2.1	2.1	0.7	0.4	0.0	5.3
	17	0.2	3.9	1.1	0.0	0.0	5.2
Subtotal		**184.0**	**247.2**	**98.9**	**48.3**	**1.0**	**579.3**
Total		523.2	1430.8	991.2	857.4	63.0	3865.6

Table 17: Outcome table of clusters of hot and coldspot and random distribution of ACCI values at a threshold radius of 178 m. This table shows the relative area (%) composition of forest (classified by fire severity class) of every cluster given by Hot Spot Analysis (Getis-Ord Gi). Shadowed cells highlight the cold (blue) and hot (red) spot examples.*

Clusters type	Cluster ID	Fully stocked	Burned	Severely burned	Very severely burned	Bare land	Weighted ACCI
Coldspot	31	6.0	11.4	24.3	51.8	6.6	22.2
	23	4.0	20.5	28.1	35.8	11.7	24.5
	21	10.7	10.3	24.0	50.3	4.7	25.4
	22	2.1	23.1	29.0	30.2	15.6	23.9
	28	0.1	24.4	40.1	26.3	9.1	25.4
	27	0.7	21.4	38.1	36.9	2.9	24.9
	34	6.0	23.0	15.3	51.9	3.7	25.6
	32	0.0	21.3	36.0	38.6	4.1	23.9
	26	0.0	21.1	23.5	53.7	1.8	22.0
	24	2.3	8.9	30.8	57.9	0.0	20.3
	30	0.0	7.1	60.8	32.1	0.0	22.8
	35	11.3	17.5	13.2	56.9	1.2	27.2
	29	0.0	24.4	47.1	24.7	3.8	27.0
	33	0.0	5.7	43.2	49.1	2.0	19.2
	25	0.0	0.0	14.0	86.0	0.0	12.3
Random	36	11.4	41.3	26.4	20.4	0.6	38.9
	38	11.9	40.6	29.5	17.7	0.3	39.6
	43	20.4	14.2	33.3	29.1	2.9	35.7
	41	10.0	13.0	31.3	43.3	2.4	27.4
	39	26.3	43.9	17.0	12.8	0.0	49.4
	37	9.6	14.1	22.4	53.8	0.0	26.3
	44	25.1	31.8	23.3	19.9	0.0	44.7
	42	8.7	23.3	39.8	23.9	4.3	31.7
	40	4.7	65.7	12.3	15.6	1.7	41.2
Hotspot	1	40.1	35.5	13.0	11.3	0.1	55.5
	15	31.6	40.4	16.8	11.1	0.1	51.8
	10	32.3	47.3	16.5	3.9	0.0	55.0
	4	23.9	47.8	22.3	5.5	0.4	50.0
	2	25.8	48.8	19.1	6.3	0.0	51.3
	6	34.4	42.9	16.4	5.0	1.3	54.6
	16	25.3	53.1	14.1	7.0	0.6	51.7
	3	27.6	42.4	18.2	11.8	0.0	49.9
	11	22.2	43.8	28.8	5.2	0.0	48.3
	13	28.6	46.3	11.9	13.1	0.0	51.2
	18	28.7	55.5	10.9	4.9	0.0	54.7
	14	25.3	44.0	24.2	6.5	0.0	49.8
	7	16.5	44.3	37.6	1.6	0.0	45.8
	12	23.1	46.6	23.8	5.1	1.4	49.1
	8	37.9	52.1	10.0	0.0	0.0	59.9
	5	20.9	45.1	19.3	14.7	0.0	46.3
	19	42.8	5.8	46.9	4.4	0.0	51.3
	9	16.1	60.5	15.9	7.4	0.0	48.3
	20	39.4	40.0	13.6	7.1	0.0	56.8
	17	4.4	75.0	20.6	0.0	0.0	46.2

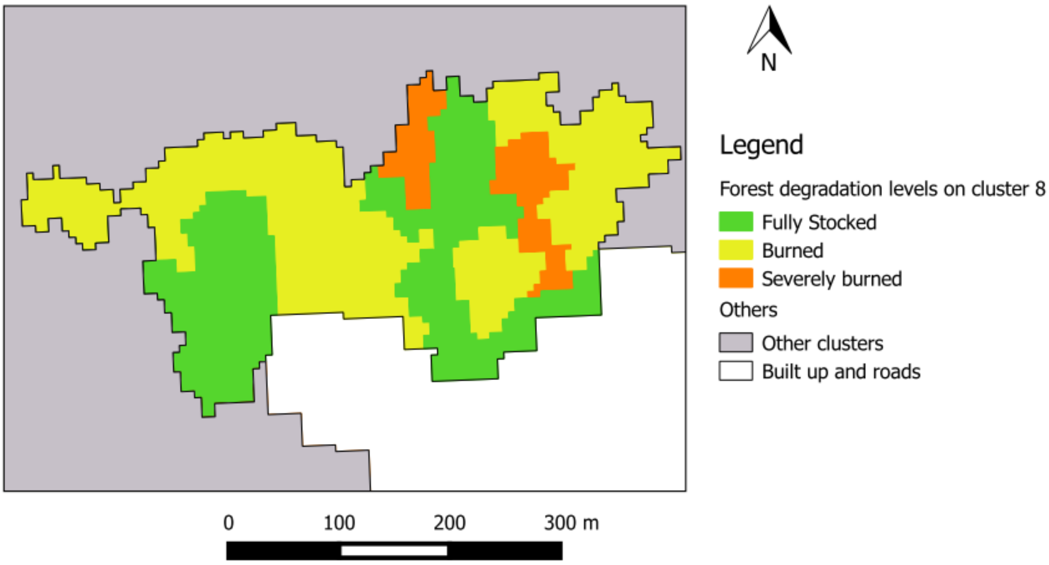


Figure 32: Composition of the cluster 8 from first scale of hotspot analysis (178 m). In the figure it can be appreciated that this hotspot cluster is composed mainly of classes with medium to high ACCI values ('fully stocked' and 'burned' forest) and fewer areas of extremely degraded forest.

In Table 18, overall results of the clustering are shown discriminated only by level of degradation (without individual cluster composition). As expected, the proportional participation of the strata 'fully stocked' and 'burned' forest is bigger on hotspots than on coldspots; whereas it is the other way around for the strata 'severely burned,' 'very severely burned,' and 'bare land.' After the elimination of the clusters smaller than 5 ha, the minimum areas of the cluster are 6.5 ha and 5.2 ha, and the average size of the cluster is 40.6 and 29.0 ha for cold and hotspot, respectively. The built-in functionality 'eliminate polygons' from the environment ArcGIS 10.3 works by assigning the eliminated polygon area to the biggest neighbouring cluster, regardless of the type of cluster this neighbour is. It explains why, after elimination of clusters smaller than 5 ha, there are 4.6, 35.1, and 78.6 ha clustered with 90, 95, and 99 % of confidence, respectively, classified as 'random' areas, and why 22.9 and 19.1 ha are clustered as cold and hotspots, when they were previously classified as not significantly clustered (Table 19).

Table 18: Outcome composition of areas discriminated by level of degradation at the overall clustered map for the hotspot analysis at 178 m distance threshold. Plain values are in hectares, and values in brackets are percentage. Av. refers to 'average area,' and SB and VSB refers to the strata 'severely burned' and 'very severely burned, respectively.

Cluster type	Fully stocked	Burned	SB	VSB	Bare land	Av.	Min area	Max area	Total Area
Coldspot (Low ACCI)	28.0 (4.6)	99.6 (16.3)	170.3 (27.9)	265.0 (43.5)	46.8 (7.7)	40.6	6.5	180.0	609.7
Random	311.2 (11.6)	1084.0 (40.5)	722.0 (27.0)	544.1 (20.3)	15.2 (0.6)	297.4	5.5	2157.6	2676.6
Hotspot (High ACCI)	184.0 (31.8)	247.2 (42.7)	98.9 (17.1)	48.3 (8.3)	1 (0.2)	29.0	5.2	179.0	579.3

Table 19: Outcome composition of areas discriminated by level of confidence on the overall clustered map for the hotspot analysis at 178 m distance threshold. Plain values are in hectares, and values in brackets are percentage. 'Be.' and 'Af.' represent the composition before and after the elimination of clusters smaller than 5 ha.

Cluster type	99 % confidence		95 % confidence		90 % confidence		Not significant		Total	
	Be.	Af.	Be.	Af.	Be.	Af.	Be.	Af.	Be.	Af.
Coldspot (Low ACCI)	299.1	296.3 (48.6)	202.5	185.1 (30.4)	133.6	105.3 (17.3)	0	22.9 (3.8)	635.2	609.7
Random	0	4.6 (0.2)	0	35.1 (1.3)	0	78.6 (2.9)	1602.2	2558.3 (95.6)	2602.2	2776.6
Hotspot (High ACCI)	208.9	207.1 (35.7)	214.3	196.5 (33.9)	207.3	156.6 (27.0)	0	19.1 (3.3)	630.5	579.3

Figure 33 shows the results of the hotspot analysis conducted with a distance threshold of 252 m. This map shows that new clusters are established from the previous scenario (for instance clusters 28 and 5). However, the total number of clusters is reduced by ten, due to the aggregation of other neighbouring clusters (for example clusters 11 and 13 from Figure 30, to cluster 7 in Figure 33). This aggregation is done by the inclusion of random areas between clusters in the previous scale of analysis, resulting in bigger but less homogeneous clusters. For hotspots (high values of ACCI) it means that the weighted ACCI value is reduced, whereas it is increased in the case of coldspots. In principle, it sounds logical that increasing the scale of analysis results in larger and less homogeneous clusters. However, this tendency has some local exceptions due to the spatial agreement of neighbouring features. For instance, cluster 27 is more homogenous and smaller at the scale analysis of 309 m than at 252 m: 24.6 of weighted ACCI at 309 m analysis, from 25.7 at 252 m of analysis (Annex 4). This tendency is kept for this cluster across the distance thresholds 252, 309, and 357m. At the fourth distance threshold scenario, the weighted ACCI is 23.5, which is desirable, but contradictory to the overall tendency. For the hotspot example (cluster 8), the weighted ACCI follows the expected tendency of losing homogeneity across the gradient (from the first to the last distance thresholds analysis; Annex 4).

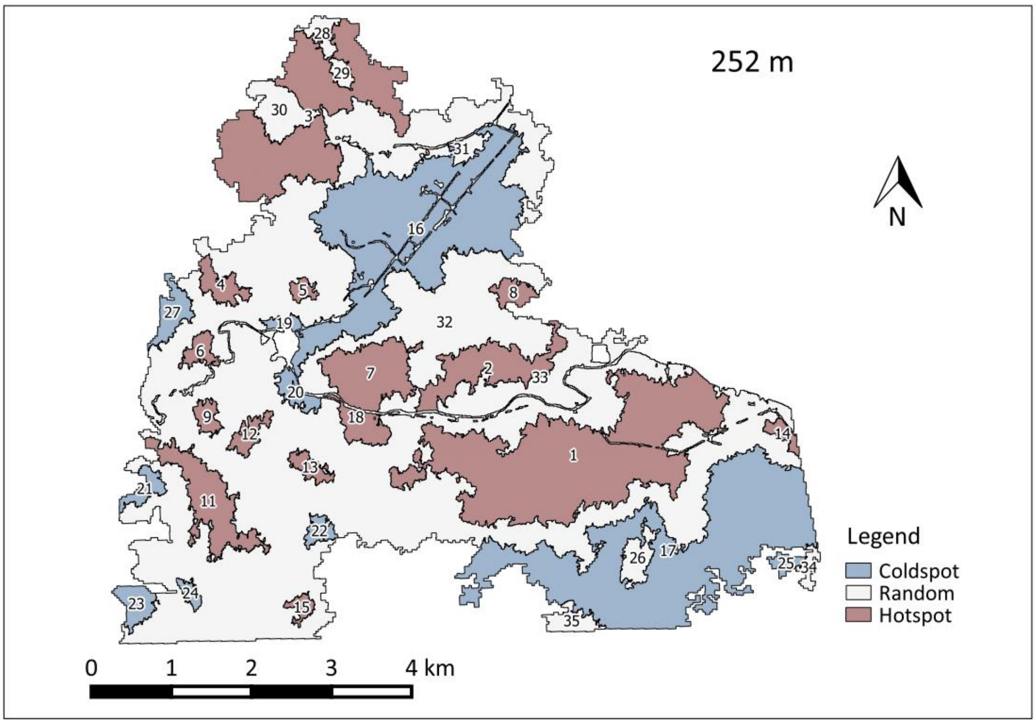


Figure 33: Hot Spot Analysis (Getis-Ord Gi) of ACCI values at a distance threshold of 252 m (20 ha). Red areas (hotspots) show clusters of high ACCI values, while blue area (coldspots) show areas of features with low values on ACCI. All features are larger than 5 ha, since smaller features were eliminated. The numbers show the feature's ID.*

Table 20: Outcome composition of areas discriminated by level of degradation at the overall clustered map for the hotspot analysis at 252 m distance threshold. Plain values are in hectares, and values in brackets are percentage. Av. refers to 'average area,' and SB and VSB refers to the strata 'severely burned' and 'very severely burned, respectively.

Cluster	**Fully stocked**	**Burned**	**SB**	**VSB**	**Bare land**	**Av.**	**Min area**	**Max area**	**Total Area**
Coldspot (Low ACCI)	51.9 (6.1)	160.4 (18.7)	249.4 (29.1)	345.5 (40.3)	50 5.8)	85.7	6.1	404.0	857.3
Random	228.1 (11.1)	854.7 (41.6)	555.7 (27.0)	405.1 (19.7)	11.4 (0.6)	205.5	7.4	1612.6	2054.9
Hotspot (High ACCI)	243.2 (25.5)	415.7 (43.6)	186.0 (19.5)	106.9 (11.2)	1.7 (0.2)	63.6	7.1	387.2	953.4

Table 21: Outcome composition of areas discriminated by level of confidence on the overall clustered map for the hotspot analysis at 252 m distance threshold. Plain values are in hectares, and values in brackets are percentage. 'Be.' and 'Af.' represent the composition before and after the elimination of clusters smaller than 5 ha.

Cluster type	**99 % confidence**		**95 % confidence**		**90 % confidence**		**Not significant**		**Total**	
	Be.	**Af.**	**Be.**	**Af.**	**Be.**	**Af.**	**Be.**	**Af.**	**Be.**	**Af.**
Coldspot (Low ACCI)	560.1	558.9 (65.2)	191.9	184.3 (21.5)	107.7	93.8 (10.9)	0	20.3 (2.4)	859.8	857.3
Random	0	2.6 (0.1)	0	19.4 (0.9)	0	36.8 (1.8)	2029.4	1996.2 (7.1)	2029.4	2054.9
Hotspot (High ACCI)	490.5	489.1 (51.3)	310.0	298.2 (31.3)	178.2	154.9 (16.2)	0	11.2 (1.2)	978.7	953.4

In Table 18, Table 20, Table 23, and Table 25, clustered areas vary from 609.7 ha related to coldspots with an average area of 40.6 ha per coldspot cluster (15 clusters) at the first scale of analysis (178 m), to 1036.4 ha (7 cluster at an average of 148.1 ha) at the fourth scale of analysis (357 m). This reduction in the number of clusters and increments in their areas is constant for hot and coldspots while increasing the threshold distance (Table 22). Even though the clusters are larger than practitioners expected, there is a big variation in their size: many small clusters and fewer large ones.

Table 22: Total clustered areas as hot or coldspots of ACCI values across the four threshold distances in hectares and percentage of the total area analysed (3865.6 ha).

Distance threshold	Total clustered area (ha)	Total clustered area (%)	Average area of clusters (ha)
178	1189.1	30.7	33.9
252	1810.7	46.8	72.4
309	2169.3	56.1	80.5
357	2354.6	60.8	138.5

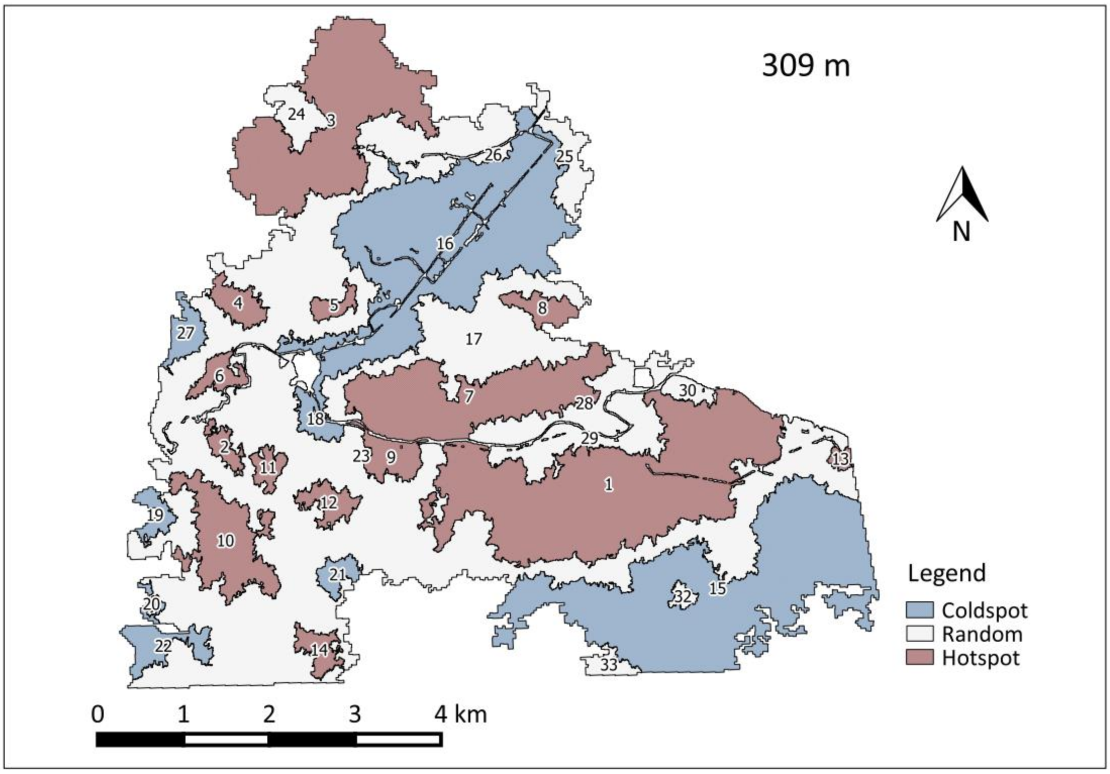


Figure 34: Hot Spot Analysis (Getis-Ord Gi) of ACCI values at a distance threshold of 309 m (30 ha). Red areas (hotspots) show clusters of high ACCI values, while blue area (coldspots) show areas of features with low values of ACCI. All features are larger than 5 ha, since smaller features were eliminated. The numbers show the feature's ID.*

Table 23: Outcome composition of areas discriminated by level of degradation at the overall clustered map for the hotspot analysis at 309 m distance threshold. Plain values are in hectares, and values in brackets are percentage. Av. refers to 'average area,' and SB and VSB refers to the strata 'severely burned' and 'very severely burned, respectively.

Cluster	Fully stocked	Burned	SB	VSB	Bare land	Av.	Min area	Max area	Total Area
Coldspot (Low ACCI)	63.3 (6.4)	207.6 (21.1)	280.8 (28.5)	381.4 (38.7)	52.4 (5.3)	123.2	5.9	454.8	985.5
Random	189.4 (11.2)	704.4 (41.5)	464.9 (27.4)	329.9 (19.5)	7.6 (0.4)	154.2	5.8	1219.8	1696.2
Hotspot (High ACCI)	270.4 (22.8)	518.8 (43.8)	245.4 (20.7)	146.1 (12.3)	3.1 (0.3)	84.6	5.4	452.1	1183.8

Table 24: Outcome composition of areas discriminated by level of confidence on the overall clustered map for the hotspot analysis at 309 m distance threshold. Plain values are in hectares, and values in brackets are percentage. 'Be.' and 'Af.' represent the composition before and after the elimination of clusters smaller than 5 ha.

Cluster type	99 % confidence		95 % confidence		90 % confidence		Not significant		Total	
	Be.	Af.	Be.	Af.	Be.	Af.	Be.	Af.	Be.	Af.
Coldspot (Low ACCI)	693.2	692.4 (70.3)	170.7	169.4 (17.2)	112.9	105.4 (10.7)	0	18.4 (1.9)	976.9	985.5
Random	0	0.7 (0.0)	0	8.1 (0.5)	0	25.3 (1.5)	1705.3	1696.2 (98.0)	1705.3	1696.2
Hotspot (High ACCI)	684.6	684.6 (57.8)	301.1	293.9 (24.8)	200.0	182.3 (15.4)	0	23.0 (1.9)	1185.7	1083.8

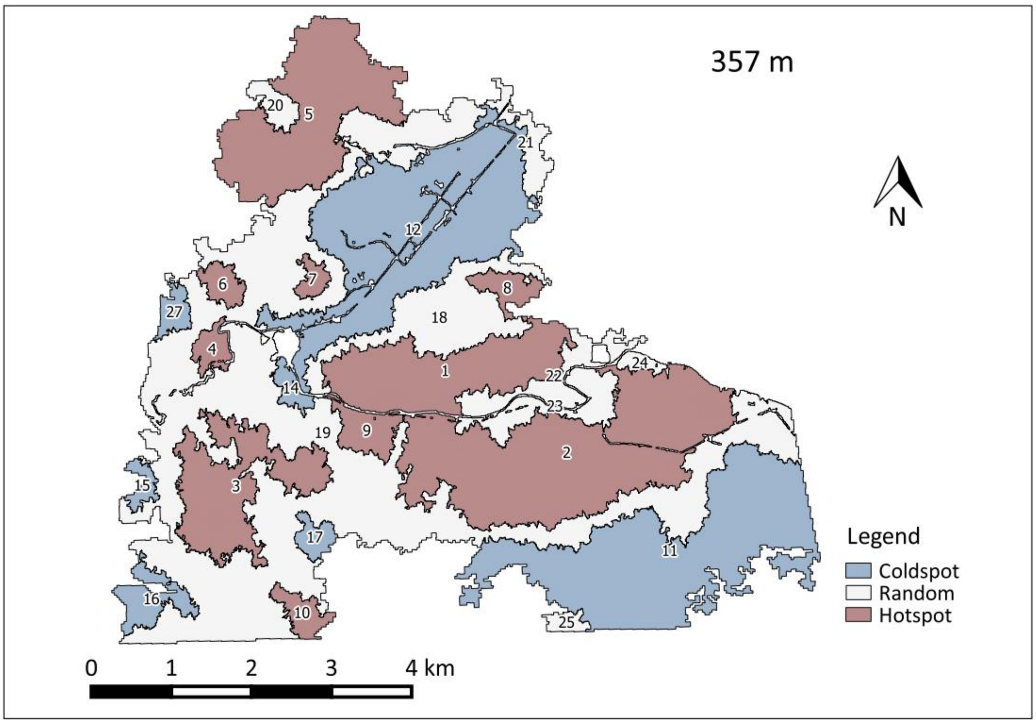


Figure 35: Hot Spot Analysis (Getis-Ord Gi) of ACCI values at a distance threshold of 357 m (40 ha). Red areas (hotspots) show clusters of high ACCI values, while blue area (coldspots) show areas of features with low values of ACCI. All features are larger than 5 ha, since smaller features were eliminated. The numbers show the feature's ID.*

Table 25: Outcome composition of areas discriminated by level of degradation at the overall clustered map for the hotspot analysis at 357 m distance threshold. Plain values are in hectares, and values in brackets are percentage. Av. refers to 'average area,' and SB and VSB refers to the strata 'severely burned' and 'very severely burned, respectively.

Cluster	**Fully stocked**	**Burned**	**SB**	**VSB**	**Bare land**	**Av.**	**Min area**	**Max area**	**Total Area**
Coldspot (Low ACCI)	68.4 (6.6)	226.3 (21.8)	297.6 (28.7)	391.2 (37.7)	52.9 (5.1)	148.1	14.1	465.1	1036.4
Random	166.7 (11.0)	620.4 (41.1)	415.3 (27.5)	302.0 (20.0)	6.6 (0.4)	188.9	10.2	1149.5	1511.1
Hotspot (High ACCI)	288.1 (21.9)	584.1 (44.3)	278.3 (21.1)	164.2 (12.5)	3.5 (0.3)	131.8	14.7	487.7	1318.2

Table 26: Outcome composition of areas discriminated by level of confidence on the overall clustered map for the hotspot analysis at 357 m distance threshold. Plain values are in hectares, and values in brackets are percentage. 'Be.' and 'Af.' represent the composition before and after the elimination of clusters smaller than 5 ha.

Cluster type	99 % confidence		95 % confidence		90 % confidence		Not significant		Total	
	Be.	Af.	Be.	Af.	Be.	Af.	Be.	Af.	Be.	Af.
Coldspot (Low ACCI)	787.75	785.8 (75.8)	163.0	160.8 (15.5)	79.4	76.6 (7.4)	0	13.2 (1.3)	1030.1	1036.4
Random	0	1.6 (0.1)	0	12.3 (0.8)	0	24.7 (1.6)	1508	1472.4 (97.4)	1508.0	1511.1
Hotspot (High ACCI)	797.6	797.5 (60.5)	335.7	325.5 (24.7)	196.4	174.3 (13.2)	0	20.8 (1.6)	1329.7	1318.2

Increments in size are accompanied by a more confident assignation of features to clusters, since the more features considered for the statistical analysis, the more confidence they give to the analysis. That is exposed on Table 19, Table 21, Table 24, and Table 26, where the confidence values of the assignment of features to clusters are sorted by coldspot, random areas, and hotspot.

It is desirable for the hotspot to have the most area of 'fully stocked' forest, and the coldspot to have the most area of 'very severely burned' forest. However, losses in homogeneity for coldspot result in a decrease from 43.5 % of 'very severely burned' forest at the first scale of analysis to 40.3 %, 38.7 %, and 37.8 % at the second, third, and fourth scales of analysis, respectively. For hotspots at the first scale of analysis, 31.8 % of the area is related to 'fully stocked' forest. This proportion is reduced to 25.5 %, 22.8 %, and 21.9 % at the second, third, and fourth scales of analysis, respectively. Those variations are shown graphically for coldspot, random, and hotspot in Figure 36.

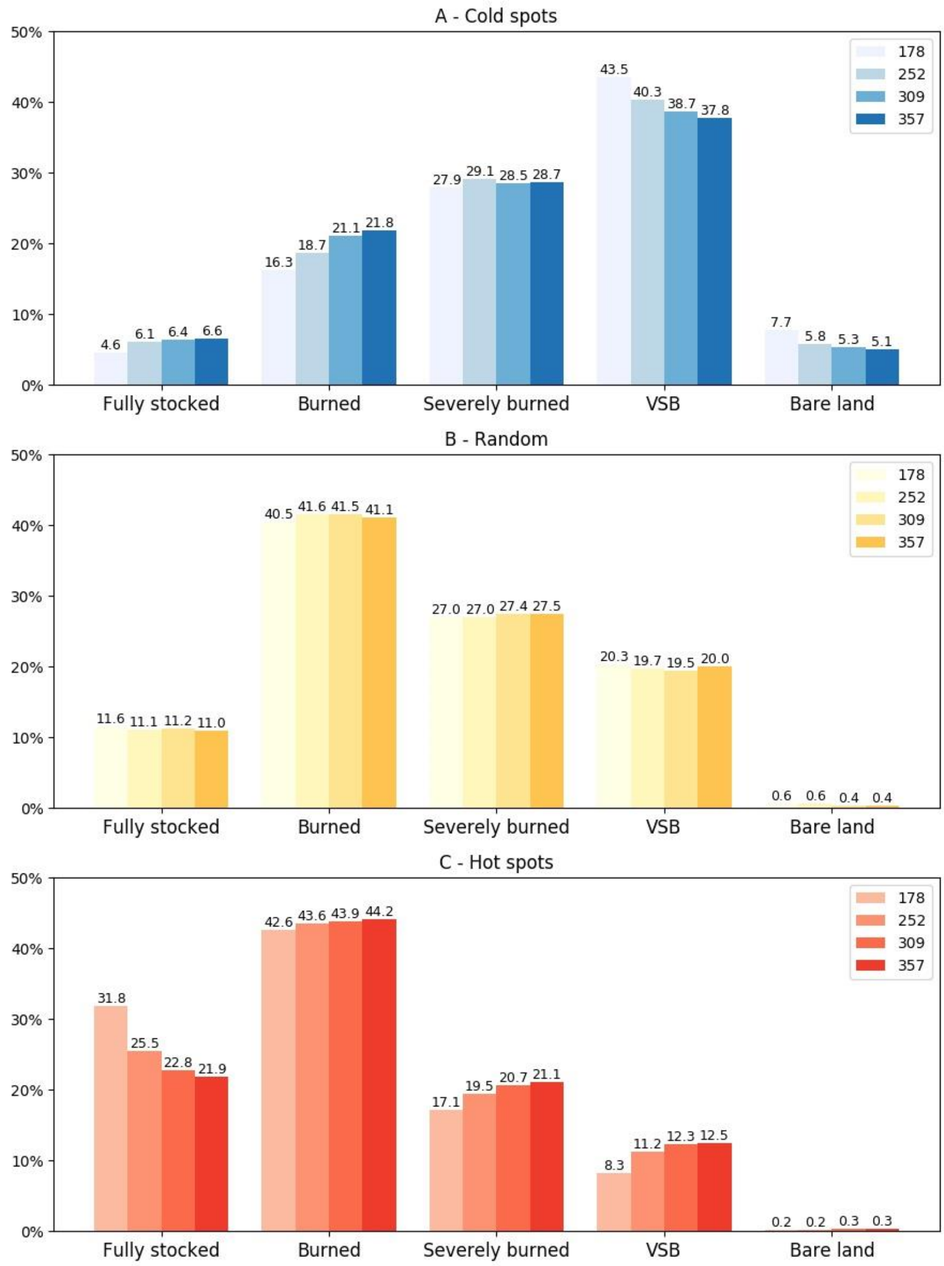


*Figure 36: Final composition of the overall obtained coldspots (**A**), random areas (**B**) and hotspots (**C**), based on the five classes of forest cover: 'fully stocked,' 'burned,' 'severely burned,' 'VSB,' and 'bare land.'*

To measure the trade-off between bigger areas (which allow for an easier and more practical implementation of silvicultural measures), and more homogeneous areas, an analysis was conducted classifying every stand as 'correctly clustered' or 'incorrectly clustered' (Table 27). Correctly clustered are, in the case of coldspots, stands from the strata 'bare land,' 'severely burned,' or 'very severely burned,' whereas 'fully stocked' and 'burned' features are clustered correctly as hotspots.

At the first scale of analysis, 30.7 % (1,189 ha) of the area is clustered either as hot or coldspots. Across the threshold distance gradient, this value changes to 60.8 % (Table 22). This increment in total clustered area of 30.1 percent-points of the site is represented by an increment of 18.1 percent-points of correctly clustered areas, and 12 percent-points of incorrectly clustered areas (Table 27). The statistics related to the correctly clustered stands (strata assigned to the desirable cluster) and to the incorrectly clustered stands (strata assigned to the wrong clusters) are reported in Table 27 and Figure 37 .

Table 27: Total area in hectares and percentage of correctly and incorrectly clustered stands across the distance thresholds. 'Cor. clustered' are correctly clustered areas and 'Incor. clustered' are incorrectly clustered areas.

Category	Area (ha)	Percentage of total site (%)	Increment based on total site area -ha- (%)	Sum of increments (%)
Cor. clustered at 178 m	913.3	23.6	---	18.1
Cor. clustered at 252 m	1303.8	33.7	390.5 (10.1)	
Cor. clustered at 309 m	1503.8	38.9	200 (5.2)	
Cor. clustered at 357 m	1613.9	41.7	110.1 (2.8)	
Incor. clustered at 178 m	275.8	7.1	---	12.0
Incor. clustered at 252 m	506.9	13.1	231.1 (6.0)	
Incor. clustered at 309 m	665.5	17.2	158.6 (4.1)	
Incor. clustered at 357 m	740.7	19.1	74.5 (1.9)	

Choosing specific distance thresholds as a general rule to be applied exceeds the objectives of this dissertation. This discussion might be implemented for every special case, and according with the objectives of the establishment of management units. However, due to the operational point of view of this research, the most adequate option would be to obtain the largest cluster possible, as long as the total of correctly clustered areas exceeds the total of incorrectly clustered areas. The ratio between the correctly and incorrectly clustered areas expresses how many correctly clustered per incorrectly clustered hectares is obtained from the analysis. It can be observed that at all analysed scales, the correctly clustered areas are double (or more) than the incorrectly clustered areas for both cold and hotspots. Furthermore, at all four scales of analysis, the percentage based increment of the total area for the 'correctly clustered' areas is always higher than the increment of the 'incorrectly clustered' areas (Table 27), indicating a positive result of increasing the distance threshold.

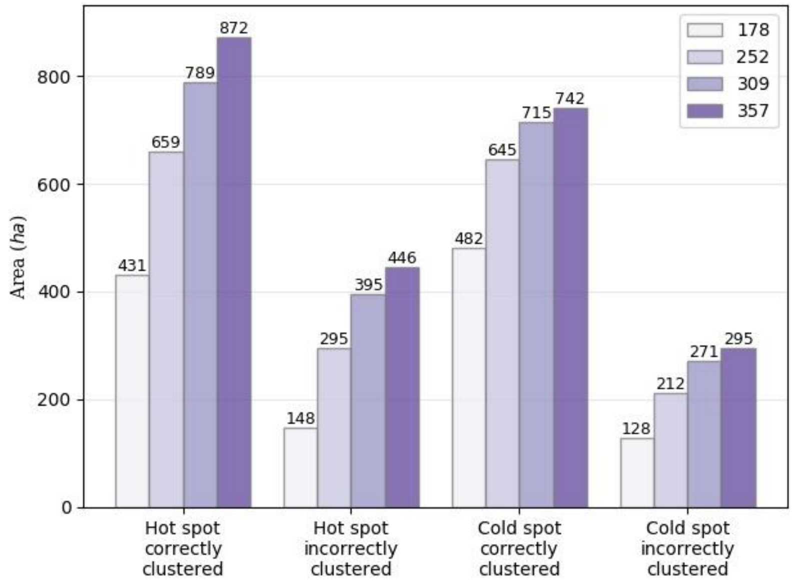


Figure 37: Trade-off for correctly and incorrectly clustered areas across the distance threshold gradient.

5.3.3 *Landscape connectivity analysis applied to FMUs*

The impact caused by the management on landscape connectivity was assessed using the software CONEFOR Sensinode 2.2 (CS22). This analysis was accomplished under the assumption that coldspots would need intensive management, applying rehabilitation techniques (such as enrichment planting [EP]), whereas in forest areas related to hotspot areas, conventional forest management (for example thinning, pruning) would be applied. Therefore, it would be desirable that the most important 'fully stocked' stands (also called nodes) in terms of their contribution to the overall connectivity, were clustered as hotspots. Otherwise, rehabilitation measures on coldspots may require the logging of 'fully stocked' stands.

Two scales of analysis were selected (178 m and 357 m) as reference seed dispersal distances, and the analysis was conducted based on the integral index of connectivity (IIC) as a measure of connectivity. This analysis weighs the node area and the number of possible links between this node and other nodes in the established distance thresholds (Saura & Pascual-Hortal 2007). The bigger the IIC value, the more important the participation of the respective node to landscape connectivity. The output supported the creation of maps (Figure 38 and Figure 39), which were overlaid with the maps resulting from the clustering analysis. This allowed to assess whether the clustering analysis includes or does not include the most relevant 'fully stocked' stands in terms on their contribution to the overall landscape connectivity into hotspot clusters.

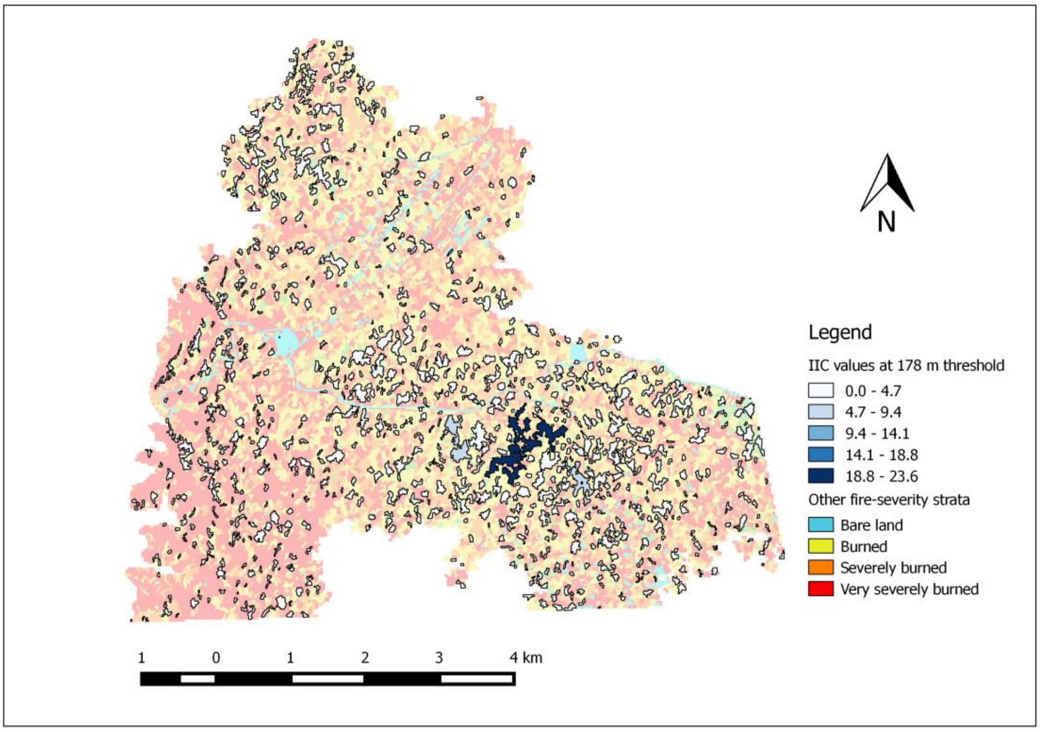


Figure 38: Ranking of node importance based on the IIC from the software CONOFOR. The bigger the value, the more important the node for the overall landscape connectivity. Used distance threshold: 178m.

The resulting maps were overlaid with the maps obtained from the establishment of FMUs based on 178 m and 357 m as distance thresholds. For each of the two output rankings (one per seed dispersal distance), it was tested whether the 50 % most important nodes were clustered as hot or coldspot. In other words, the 50 % (261.8 ha) most important 'fully stocked' stands in terms of their contribution to the connectivity were selected. The result should reveal which share (in area %) of the ecologically most important areas would be at risk of being included in areas dedicated to intensive management activities, i.e. EP with exotic species.

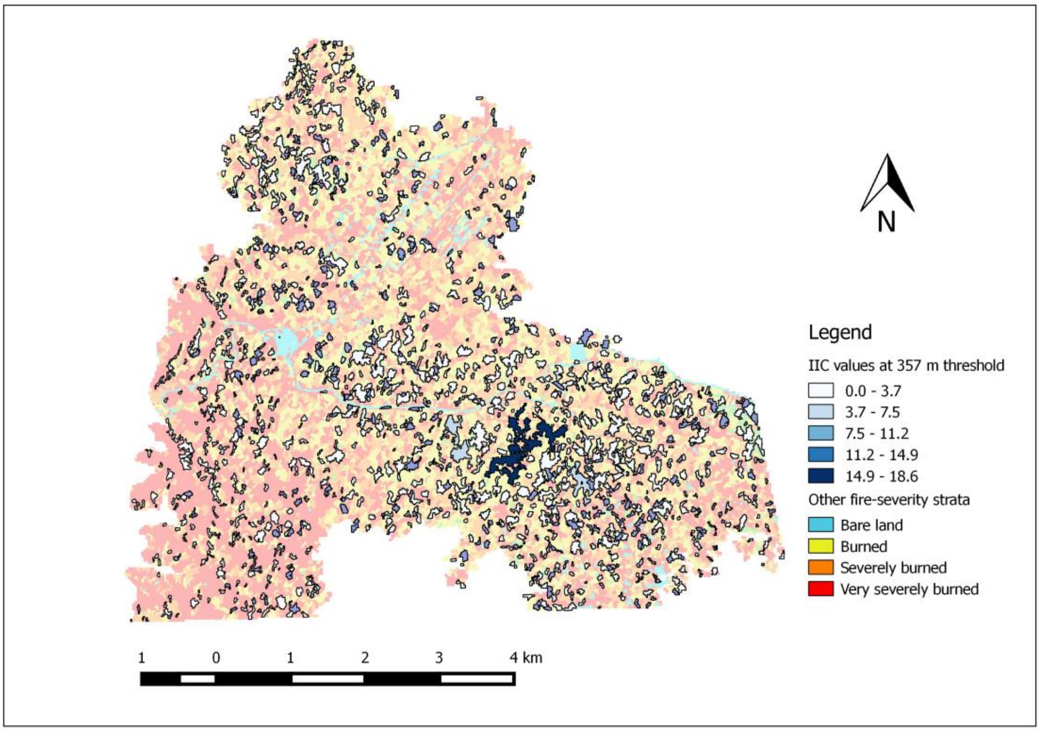


Figure 39: Ranking of node importance based on the IIC from the software CONOFOR. The bigger the value, the more important is the node for the overall landscape connectivity. Set distance threshold: 357m.

Table 28 shows that between the two distances used for the connectivity analysis, only a slightly different selection of areas is accomplished. However, at the same distance threshold on the connectivity analysis, bigger differences are found for the different thresholds used for cluster analysis. Considering the map of FMUs established from the distance threshold of 178 m, approximately 50 % of the most important areas for landscape connectivity are clustered as hotspots. At a distance threshold of 357 m, the inclusion of these ecologically important areas is significantly increased to approximately 70 %. This result suggests using larger distance thresholds for the establishment of FMU.

Table 28: Overlay of the most important areas for landscape connectivity at two scales of analysis based on IIC- CONEFOR index (columns) with clusters associated to high values of ACCI (hotspots) at 178 m and 357 m of analysis (rows). Plain numbers are expressed in hectares, numbers in brackets are percentage representation of the 50 % (261.8 ha) most important areas in terms of their contribution to the overall landscape connectivity.

	Connectivity at 178 m threshold	Connectivity at 357 m threshold
Hotspots at 178 m threshold	137.5 (53.6 %)	140.7 (53.8 %)
Hotspots at 357 m threshold	184.3 (70.8 %)	188.2 (72.1 %)

Figure 40, Figure 41, Figure 42, and Figure 43 map the different distributions of the (50 %) most important nodes based on IIC index, and their intersection to the hotspots at the two selected scales of analysis. The most important stands for landscape connectivity are mainly coincident with hotspots, especially when the base map results from the use of the distance threshold of 357 m of clustering.

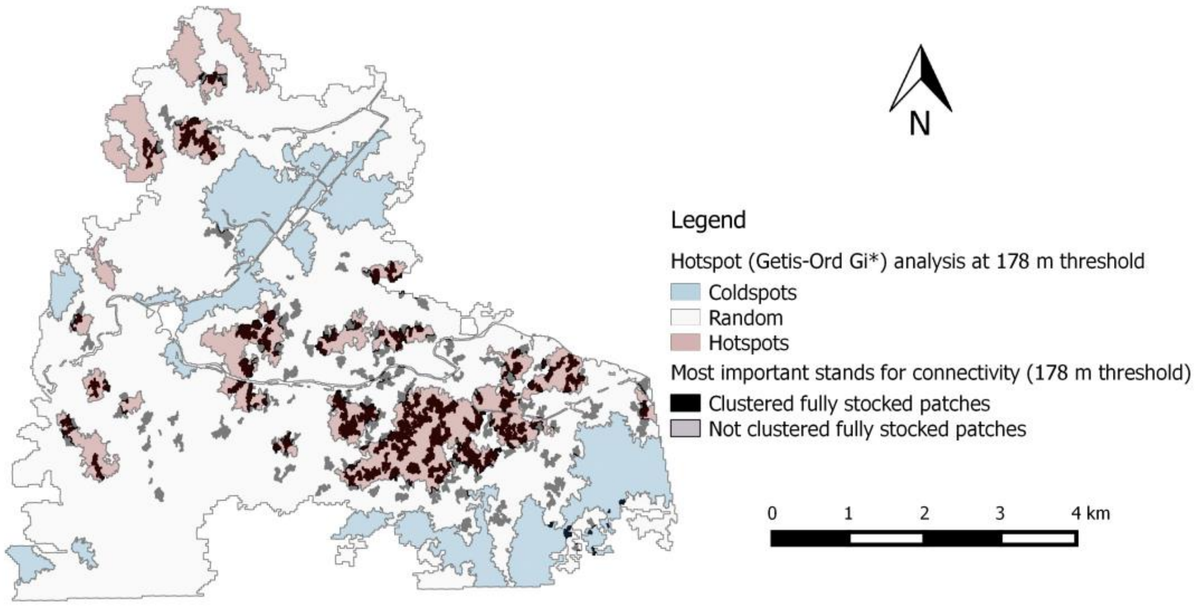


Figure 40: Overlay of the most important areas for landscape connectivity at 178 m distance threshold, conducted by IIC-CONEFOR index with clusters associated to high values of ACCI (hotspots) at 178 m of analysis.

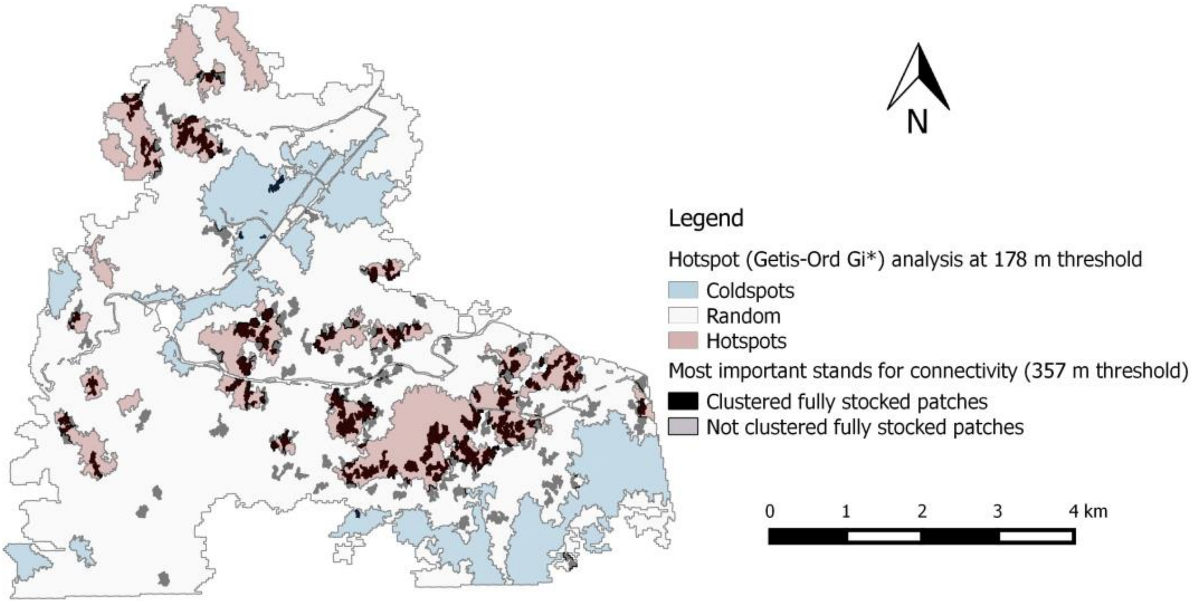


Figure 41: Overlay of the most important areas for landscape connectivity at 357 m distance threshold, conducted by IIC-CONEFOR index with clusters associated to high values of ACCI (hotspots) at 178 m of analysis.

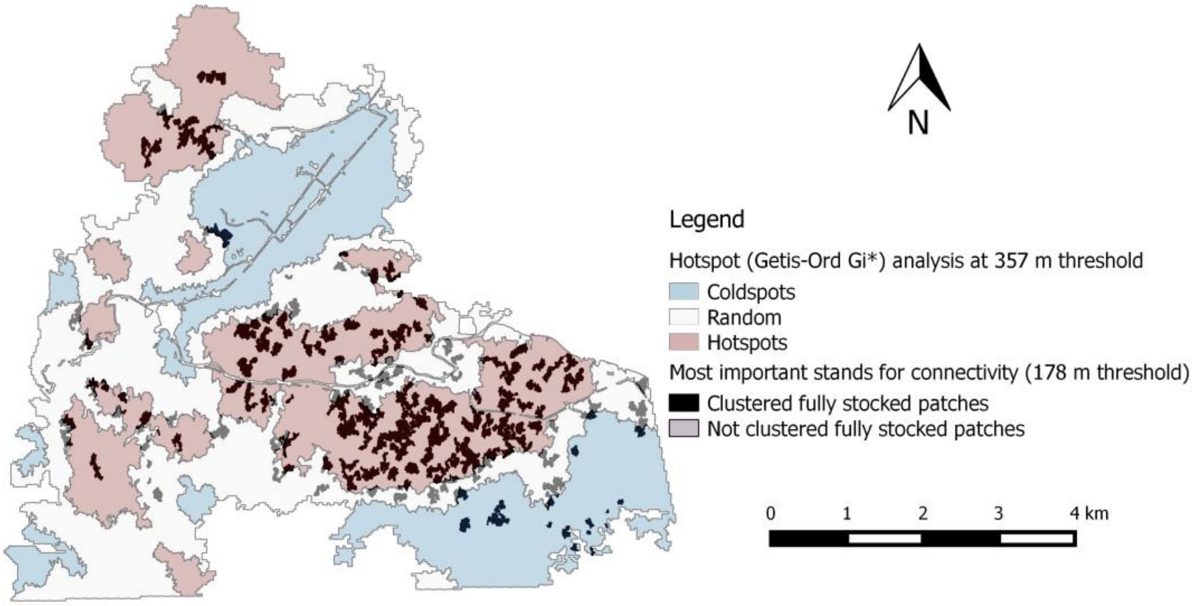


Figure 42: Overlay of the most important areas for landscape connectivity at 178 m distance threshold, conducted by IIC-CONEFOR index with clusters associated to high values of ACCI (hotspots) at 357 m of analysis.

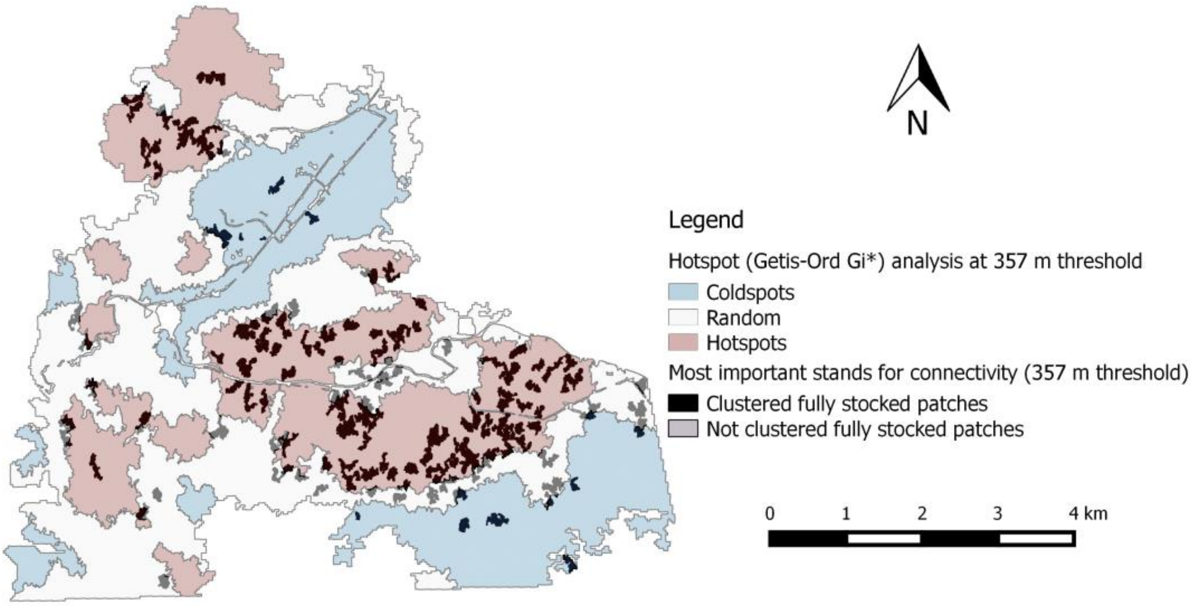


Figure 43: Overlay of the most important areas for landscape connectivity at 357 m distance threshold, conducted by IIC-CONEFOR index with clusters associated to high values of ACCI (hotspots) at 357 m of analysis.

5.4 Enrichment planting

A ground inventory on the EP in Florestoona was carried out in blocks organised based on: (1) year of plantation, (2) species composition, (3) EP design, and (4) tree lines orientation. The results are reported in Table 29, and the comparisons of results made with a Welch t-test are reported in the following boxplot figures (Figure 44, Figure 45, Figure 46, Figure 47, Figure 48, and Figure 49). Following are presented the results of the seven comparisons of means stated in the section 4.5.1 'Statistical Analysis.'

1- Species growth in the blocks planted in 2008. Comparison of the means of average growth of DBH between the species planted in the blocks ToonaParaiso2008, ToonaParaiso2008_SW, ToonaParaiso2008_sq, and Tipa2008.

This comparison is based on means of maximum, minimum, and average DBH. Mean of average growth of DBH is greater in 'tipa' (17.7 cm) than in 'toona' (13.5 cm) and 'paraíso' (10.8 cm) at the age of seven years from plantation (Figure 44). No statistically significant differences in means of average growth of DBH are present between 'toona' and 'paraíso,' nor between 'toona' and 'tipa.' There were no statistically significant differences for maximum and minimum growth in DBH, except for 'tipa,' which reported a larger mean maximum DBH (25.2 cm). The survival rate of those plots is similar for all the blocks (between 33 % and 40 %), nevertheless BA is greater, and almost double, for Tipa2008 (12 m²/ha) than for the other blocks (6.3, 8.1 and 6.5 m²/ha).

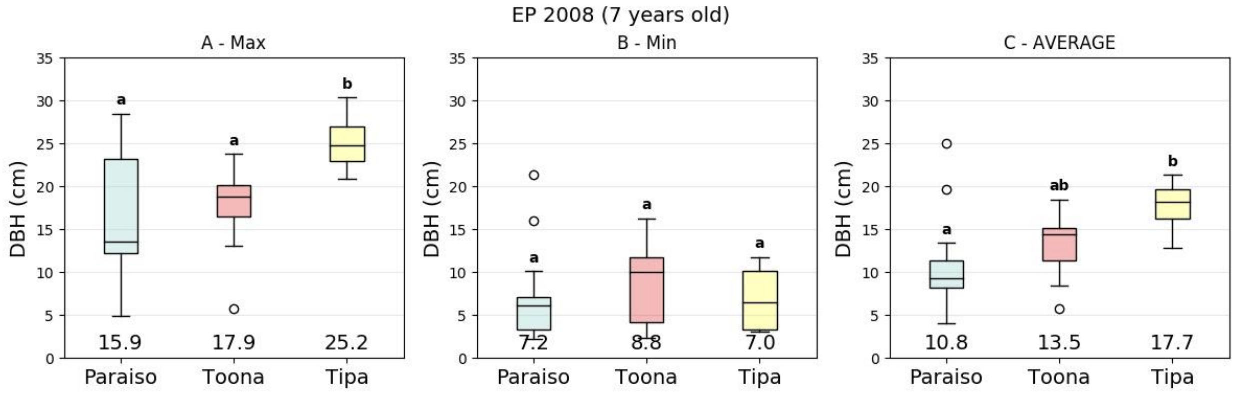


Figure 44: Species growth from EP planted in 2008. Comparison of the means of maximum, minimum, and average DBH of the blocks ToonaParaiso2008, ToonaParaiso2008_SW, ToonaParaiso2008_sq, and Tipa2008. Means are reported at the bottom of the boxes. Different letters report statistically significant differences in mean with a confidence of 95 %.

The results presented on Figure 44 can be biased due to the mixture of the species, and not the single species themselves, since 'toona' and 'paraíso' were consociated, and 'tipa' was in monospecific EP.

2- Species growth in monospecific EP. Comparison of the means of maximum, minimum, and average DBH-MAI between the species planted in the blocks Paraiso2011, ParaisoThinned2011, Toona2004, Tipa2008, and Tipa2009.

Figure 45 reports the response of the same species, all in monospecific EP. Since the age is different between the analysed blocks, DBH-MAI is considered instead of absolute DBH. In this case, the results reported a larger growth for 'paraíso' than for 'tipa' and 'toona.'

*Table 29: Overview of the results of the ground inventory conducted on the EP in Florestoona. Results are reported by block and species. * The results for 'tipa' are not reported because most of the plants had a DHB lower than 2 cm, therefore only their heights were measured.*

Block ID	**Species**	**DBH (cm)**			**BA**	**MAI (cm/year)**			**Survival**
		Min	Max	Average	**(m²/ha)**	Min	Max	Average	**factor (%)**
Toona2004	Toona	17.7	27.7	27.3	14.4	1.6	3.2	2.5	38
Tipa2008	Tipa	3.1	30.4	13.0	12.0	0.4	4.3	1.9	37
	Toona & paraíso	2.2	24.6	12.0	6.3	0.3	3.5	1.7	38
ToonaParaiso2008	Toona	2.3	20.9	13.8	2.7	0.3	3.0	2.0	--
	Paraíso	2.2	24.6	8.8	1.8	0.3	3.5	1.3	--
	Toona & paraíso	2.5	26.7	13.9	8.1	0.4	3.8	2.0	33
ToonaParaiso2008_SW	Toona	3.9	23.8	14.1	4.1	0.6	3.4	2.0	--
	Paraíso	3.2	26.7	17.5	3.9	0.5	3.8	2.5	--
	Toona & paraíso	3.5	28.5	12.9	6.5	0.5	4.1	1.8	40
ToonaParaiso2008_sq	Toona	3.5	22.8	13.9	3.6	0.5	3.3	2.0	--
	Paraíso	6.9	28.5	11.9	2.9	1.0	4.1	1.7	--
Tipa2009	Tipa	6.7	23.6	12.8	12.0	1.1	3.9	2.1	77
ParaisoThinned2011	Paraíso	14.4	26.7	20.1	5.9	2.9	5.3	4.0	23
Paraiso2011	Paraíso	11.3	26.8	18.7	13.4	2.3	5.4	3.7	59
ParaisoTipaThinned2011*	Paraíso	5.9	18.9	11.7	2.4	1.2	3.8	2.3	63

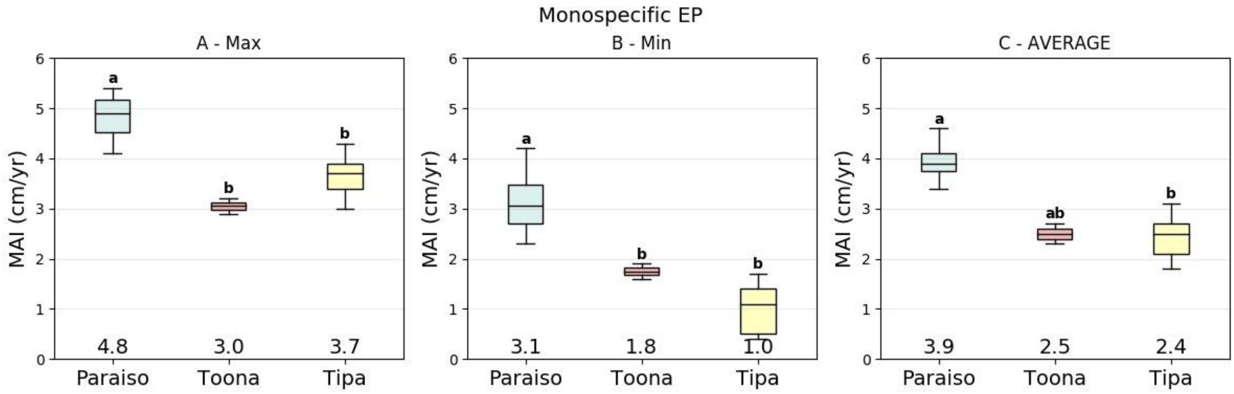


Figure 45: Species growth in monospecific EP. Comparison of the means of maximum, minimum and average DBH-MAI from the blocks Paraiso2011, ParaisoThinned2011, Toona2004, Tipa2008, and Tipa2009. Means are reported at the bottom of the boxes. Different letters report statistically significant differences in mean with a confidence of 95 %.

3- Mean growth between 'toona' in monospecific EP and 'toona' in mixed-species EP. Comparison of the means of average DBH-MAI between the block Toona2004, and the blocks ToonaParaiso2008, ToonaParaiso2008_SW, and ToonaParaiso2008_sq.

Average DBH-MAI of 'toona' planted in mixed-species EP blocks (ToonaParaiso2008, ToonaParaiso2008_SW, and ToonaParaiso2008_sq), and the monospecific EP block (Toona2004) did not show statistically significant differences (Figure 46). However, slightly greater DBH-MAI was observed for the monospecific EP (2.5 cm/y) than for the mixed-species EP (1.9 cm/y). The reported survival rate is similar for all the blocks (between 33 and 40 %), while BA is greater in monospecific EP, but probably due to the age of plantation, and not an effect of mixture of species.

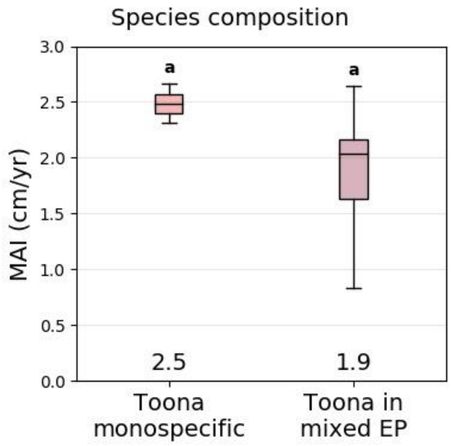


Figure 46: 'Toona' trees response to species composition. Comparison of the means of maximum, minimum and average DBH between the mixed-species EP blocks (ToonaParaiso2008, Toona-Paraiso2008_SW, and ToonaParaiso2008_sq), and monospecific EP block (Toona2004). Means are reported at the bottom of the box. Different letter report statistically significant difference in mean with a confidence of 95 %.

4- Mean growth between 'paraíso' in monospecific EP and 'paraíso' in mixed-species EP. Comparison of the means of maximum, minimum, and average DBH-MAI between the blocks Paraiso2011 and ParaisoThinned2011, and the blocks ToonaParaiso2008, ToonaParaiso2008_SW and ToonaParaiso2008_sq.

The response of 'paraíso' to species composition was compared between the mixed-species EP blocks (ToonaParaiso2008, ToonaParaiso2008_SW, and Toona-Paraiso2008_sq), and the monospecific EP blocks (Paraiso2011 and ParaisoThinned2011). Means of maximum, minimum, and average DBH-MAI are statistically greater in 'paraíso' trees planted in monospecific blocks than the ones planted associated with 'toona' (Figure 47). Survival rate is uneven for the blocks planted in 2011, since half of the EP areas have already been thinned before the measurements (ParaisoThinned2011), while the other half were not (Paraiso2011). BA of the block ParaisoThinned2011 is reduced to 44 % in comparison with the blocks which were not thinned, although mean DBH is increased only slightly (from 18.7 cm in the block Paraiso2011, to 20.1 cm in the block ParaisoThinned2011), suggesting that the growth before the thinning was homogeneous among the trees. From the results in Table 29, 'paraíso' seems to be oppressed by 'toona,' since when they are associated, 'toona' does not show different growth, whereas 'paraíso' has a much lower growth in DBH than when it grows in monospecific EP.

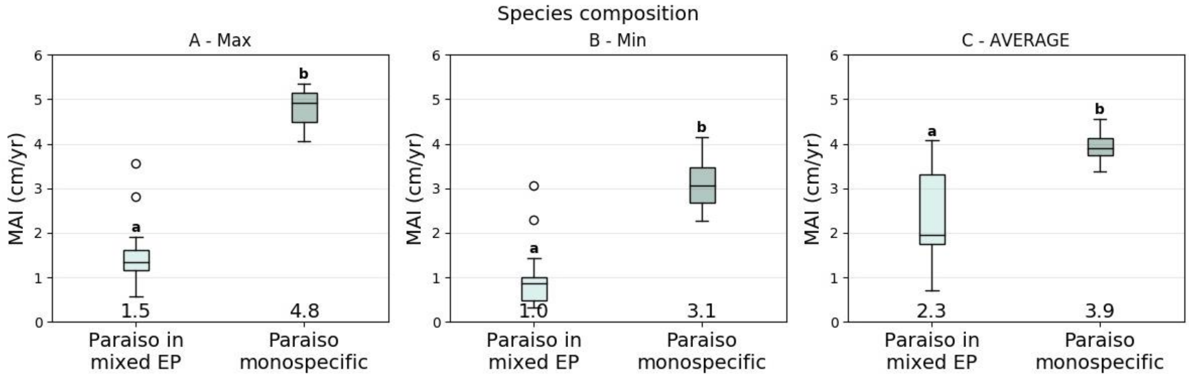


Figure 47: 'Paraíso' trees' response to species composition. Comparison of the means of maximum, minimum, and average DBH between 'paraíso' planted in mixed-species EP (blocks ToonaParaiso2008, ToonaParaiso2008_SW, and ToonaParaiso2008_sq), and monospecific EP (blocks Paraiso2011 and ParaisoThinned2011). Means are reported at the bottom of the boxes. Different letters report statistically significant differences in mean with a confidence of 95 %.

5- Planting line orientation effect on the species 'toona' and 'paraíso' in the blocks planted in 2008. Comparison of the means of maximum, minimum, and average DBH per species between the block ToonaParaiso2008_SW, and the blocks ToonaParaiso2008 and ToonaParaiso2008_sq.

Planting line orientation did not show any effect on the growth of 'toona' and 'paraíso.' Two orientations were tested for two species planted in 2008 (Figure 48). None of the comparisons (means of minimum, maximum, and average DBH) reported statistically significant differences, probably because insolation is not a limiting factor in the subtropics.

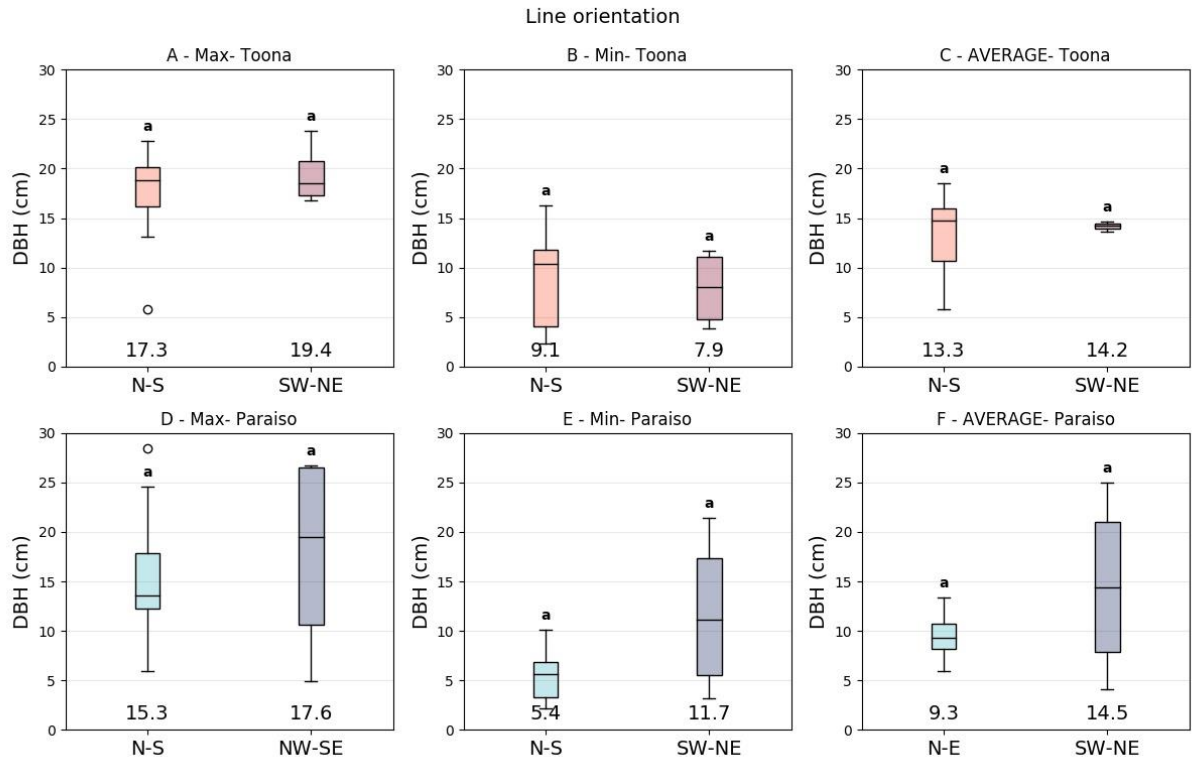


Figure 48: Species response to two tree line orientations (N-S and SW-NE). Results are reported by the comparison of the means of maximum, minimum, and average DBH of the orientation N-S (blocks ToonaParaiso2008, and ToonaParaiso2008_sq), and SW-NE (block Toona-Paraiso2008_SW). Means are reported at the bottom of the boxes. Different letters report statistically significant differences with a confidence of 95 %.

6- Planting line orientation effect of the blocks Tipa2008 (N-S) with Tipa2009 (NW – SE). Comparison of mean average DBH-MAI.

No statistical comparison of means was conducted for this case because only one plot in the block Tipa2009 was measured. The average DBH-MAIs are similar, but slightly larger for the block Tipa2009 (2.1 cm for Tipa2009, and 1.9 cm for Tipa2008), while the maximum DBH-MAI is much bigger on the Tipa2008 block. Those results show a probable effect of orientation, which cannot be confirmed due to the low number of samples. The BA is identical, however, it might be observed that the survival rate is half in the Tipa2008 block, which has already been thinned.

7- Design effect on the species 'toona' and 'paraíso.' Comparison of the means of DBH-MAI between the blocks ToonaParaiso2008_sq, Paraiso2011, ParaisoThinned2011 and Toona2004, and the blocks ToonaParaiso2008 and Toona-Paraiso2008_SW.

Species response was assessed for 'toona' and 'paraíso' planted in groups (ToonaParaiso2008_sq, Paraiso2011, ParaisoThinned2011, and Toona2004) and in strips (ToonaParaiso2008, and ToonaParaiso2008_SW). Greater growth is observed for the group EP than in strip EP for the species 'paraíso.' Mean of average DBH-MAI is more than double for 'paraíso' in the group design (3.5 cm/y) in comparison with the strip design (1.5 cm/y). Those results find justification in the proportion of areas occupied by border lines. The border lines represent close to 60 % of the 7 line EP, and 50 % of the group EP (45 m * 40 m). In those cases where strip EP is done in only 5 lines, the border effect is drastically increased to 80 % of the planted area. However, those results might not be directly attributed to design effect, since most of the blocks planted in groups are also monospecific, and the ones in strips are not, with the only exception being the block ToonaParaiso_2008_sq, which is a group EP with mixed-species. Consequently, these results are similar to the comparison of monospecific and mixed-species EP reported in Figure 46 and Figure 47 for 'toona' and 'paraíso,' respectively. Furthermore, comparing the values of DBH-MAI in Table 29, the lowest average DBH-MAI for 'paraíso' is reported for the block where both species are associated. For 'toona,' the design did not show effect on the means of minimum, maximum, and average DBH-MAI (Figure 46). In this case the additional effect of species association might not influence negatively, since 'toona' is dominant over 'paraíso' when they are associated.

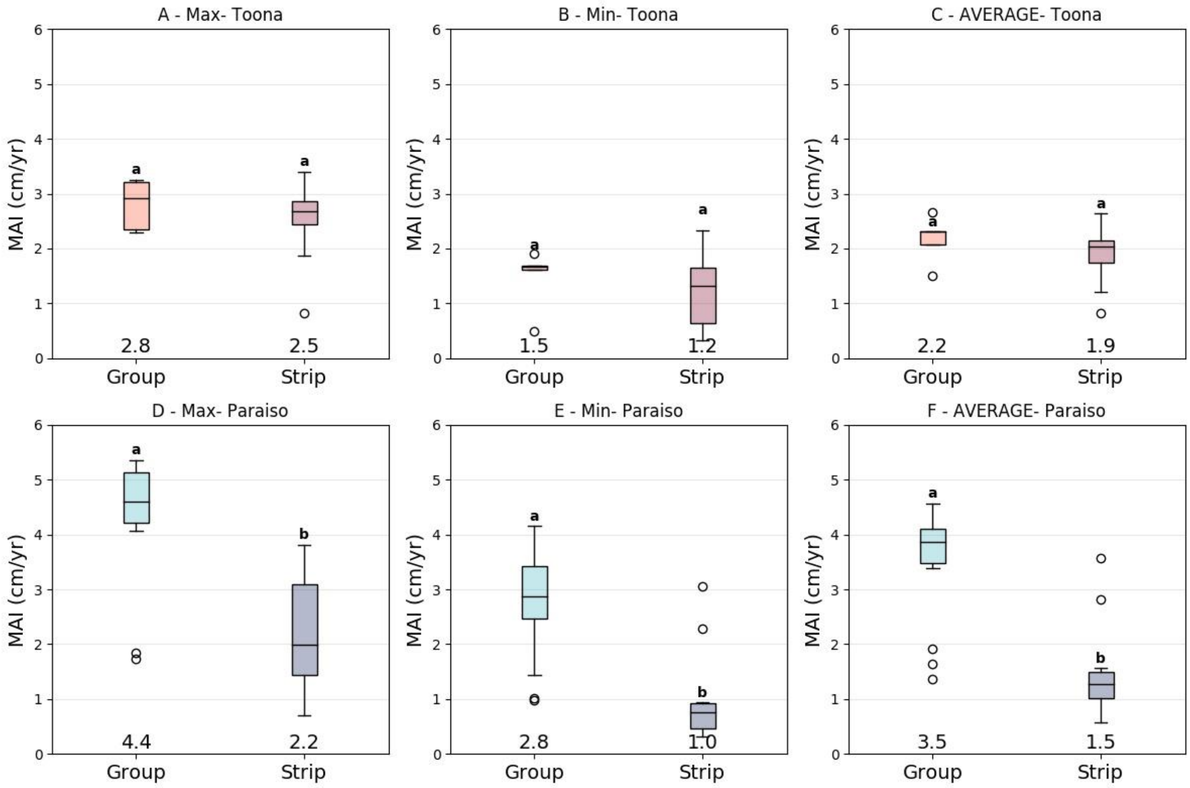


Figure 49: Species response to two tree planting designs (group and strip). Results are reported by the comparison of the means of maximum, minimum, and average DBH-MAI of group EP (blocks ToonaParaiso2008_sq, Paraiso2011, ParaisoThinned2011, and Toona2004), and strip EP (blocks ToonaParaiso2008, and ToonaParaiso2008_SW). Means are reported at the bottom of the boxes. Different letters report statistically significant differences with 95 % of confidence.

In conclusion, design effect could not be isolated from species composition effect. 'Paraíso' showed the best growth when it is planted in monospecific (and group) EP, whereas 'toona' did not report statistical differences when planted in monospecific or mixed-species EP. 'Tipa,' was not measured due to its low growth when mixed with 'paraíso,'whereas when planted in monospecific EP, did not report statistical differences to 'toona'.

6 Discussion

6.1 Image classification supported with UAV imagery

In this research, fire-induced forest degradation was addressed under operational objectives, conducting the assessment of fire-severity by its effect on forest canopy cover (Souza et al. 2005) and the reduction of forest stocks (Dunn & Bailey 2016). Reflectance data of the forest were acquired from the SPOT6 image and used for its segmentation and two classifications. The classifications of the SPOT6 image were trained with basal area (BA) data acquired from ground inventory, and with adjusted canopy cover index (ACCI). ACCI was formulated from the correlation of BA to photogrammetry-derived structure attributes (canopy cover [CC] and tree heights), which were estimated from unmanned aerial vehicle (UAV) imagery solely. ACCI is presented in this research as an alternative to CC to define classes of fire-severity strata, weighting CC from tree height classes by their influence on forest stocks (BA). ACCI equates to forest degradation, since it refers to horizontal and vertical structures of a stand, and their influence on growing stocks (Dunn & Bailey 2016). In this context, ACCI demonstrated to achieve a good prediction of fire-induced damage to forest stocks, if no quality DTM is available. This is valid only when the forest is open enough to allow the sensors to also get information about the terrain elevation.

The correlation of partial canopy cover at three tree height classes against BA had a r^2 of 0.76, the same as the results found by Bohlin et al. (2012), but higher than those found by Puliti et al. (2015), who obtained prediction of BA with a r^2 of 0.60 using a precise airborne laser scanning (ALS)-derived digital terrain model (DTM). Fraser et al. (2017) also obtained less promising results using several UAV and Landsat imagery-derived spectral indexes to predict Composite Burned Index (CBI), as an indicator of fire-severity, with a r^2 between 0.36 to 0.6. The high coefficient of determination reported in this research might be attributed to the high number of field plots, and the use of ACCI, which accounts for tree height classes instead of total CC solely.

The final aim of this research was to delineate homogeneous stands among a heterogeneously stocked forest area in order to plan its rehabilitation. In order to measure localised fire-damage, and because a detailed map of stocks of the pre-fire situation was not available, the benchmark (of BA and ACCI) were considered homogeneous along the forest before the fire, according to inventory results. BA-based and ACCI-based thresholds were then defined based on the change of the forest from the benchmark (Suding & Hobbs 2009; Thompson et al. 2013).

An area-based approach to conduct forest inventories is structured in two stages: in the first stage, ground and remotely-sensed (RS) data are correlated; in the second stage, the predictive models are applied to a wall-to-wall cover (Næsset 2002; White et al. 2013). Responding to the recommendations of Ene et al. (2016), the methodology presented in this research added a third stage, since three source data scales were used: local (ground plots), partial cover (UAV imagery) and wall-to-wall cover (satellite imagery). Adding strategically localised UAV flights to a ground inventory allowed to correlate field data with UAV-derived metrics. Therefore, the supervision of satellite image classification could be conducted on areas where no ground data was available, but only UAV-imagery. This methodology achieved a reduction of the number of outliers in the classification (stands classified incorrectly into a very different strata) in comparison with the approach where only BA from ground inventory was used for supervision. Therefore, the stratified BA-based relative estimation error of 20 % (as prescribed by the Argentinian forest directives) could be achieved by introducing additional image plots without the need for a higher number of inventory plots on the ground, which are costly, and in remote areas technically difficult to obtain. In the present case study, the aimed BA-based error was achieved with an additional 20 image plots but, depending on the objectives of the inventory, more image plots could be calculated from UAV imagery in order to improve image classification further. Puliti et al. (2018) conducted inventories with partial UAV imagery and ground inventory. Under a different perspective, with the objective of avoiding expensive UAV flights, they demonstrated that adding wall-to-wall Sentinel-2 data to their inventory (and keeping the number of sample plots constant) decreased the need for UAV cover.

Regarding the accuracy of the estimation of tree heights, three different cases must be separately analysed; the first one when the ACCI value is higher than 66 (which relates to the stratum 'fully stocked'). Individual tree heights calculated by the CHM5 without any manual correction were underestimated with a root mean squared error (RMSE) of 8.25 m, and the adjusted coefficient of determination from the correlation of the observed and estimated individual tree height was rather insignificant (0.06). The predictions improved when the CHM10 was used (RMSE: 5.49 m, r^2: 0.12), but were still not satisfactory. In general, for dense canopy cover forest areas, the results confirmed the findings of Dandois & Ellis (2010). In those cases, it is better to work with another source to calculate a precise DTM, because the errors are extrapolated to the calculation of CHM. However, in these cases of dense canopy cover, orthomosaics were used to identify the causes of the pixelation through visual inspection, and to correct it manually while estimating partial CC per tree height class (THC).

The second case is for the stratum 'burned' (with ACCI values between 33 and 66). The results found for this stratum (r^2: 0.44, RMSE: 4.20 m) are comparable with those found by Dandois & Ellis (2010) on their case study 'Knoll' using UAV imagery to estimate digital surface model (DSM) and DTM from ALS data (r^2: 0.53, RMSE: 4.31 m). Surprisingly, more accurate predictions were found by the same authors using DTM calculated from UAV imagery (r^2: 0.64, RMSE: 3.76 m). In this case, the authors attributed the error to a possible GPS limitation at calculating altitudes, complex canopy structure, and to the obstruction of the view to calculate DTM under dense canopy cover.

In another experiment, Dandois & Ellis (2010) reported better results for both cases, with DTM from UAV imagery (r^2: 0.74, RMSE: 3.28 m) and from ALS data (r^2: 0.8, RMSE: 2.88 m). Those values are similar to the findings in this research for areas with ACCI value lower than 33 (third case of analysis), where the r^2 of the correlation between observed and predicted tree heights are 0.79 and 0.8 for CHM5 and CHM10, respectively. RMSEs are also similar: 2.96 m and 2.85 m for CHM5 and CHM10, respectively. However, Lisein et al. (2013) achieved better estimations of individual tree heights using DSM from UAV, and DTM from ALS, with significantly better precision (r^2: 0.91, RMSE: 1.04 m). Also, more promising results were found by Wallace et al. (2016), who estimated CHM in relatively open Australian forest with an RMSE of 1.3 m (r^2: 0.68). However, in this case the study area was only 1,500 m^2, and the flight altitude only 30 m aboveground level, catching 425 images for the area. Such intensive acquisition of images is not feasible to be reproduced at the field scale of the present research. The same authors mentioned a reduction of precision at a higher flight altitude, and under dense canopy cover.

In summary, in this research, more accurate predictions of tree heights were obtained when the canopy cover of the stands was lower, and when the DTM has lower resolution (DTM10). The found effects of dense canopy cover are coincident to Wallace et al. (2016) and Dandois & Ellis (2013), who calculated more accurate imagery DTMs in sparse forests than in areas with dense canopy cover. However, since the automatic estimation of CC from UAV imagery would result in a big error, in this research partial CC was calculated for sample plots by the use of a sampling grid, which allowed to apply a detailed visual inspection to correct errors on CHMs.

Usually, the use of UAV imagery to assess canopy cover is recommended only if a detailed terrain model is available, since the optical sensors penetrate to the terrain only if there are gaps in the forest (Nurminen et al. 2013), as dense canopies limit the assessment of under-story objects (St-Onge et al. 2004; Dandois & Ellis 2010; Getzin et al. 2012; Merino et al. 2012; Honkavaara et al. 2013; Lisein et al. 2013; White et al. 2013; Penner et al. 2015; Wallace et al. 2016). However, in Argentina the publicly available SRTM-DTM has a resolution of 30 m/pixel, with an error of 3 m in altitude, which is far less precise than those of lower than 1 m of horizontal and 0.15 m vertical resolutions in some developed countries (Beckenbach et al. 2014; Fisher et al. 2017). In this research, a step forward to support the assessment of open forest areas was achieved, since the results found in the case study where no precise high-resolution DTM was available are very promising. Therefore, an UAV-based DTM was calculated.

The lower resolution DTM (10 m/pixel) proved to avoid many errors in the estimations of the CHM, which are frequently observed (by pixelation) on the CHM5. A wider spacing for their calculations increases the chance to reach data closer to the actual terrain, although this gain in precision is obtained at the expense of a lower resolution. For the example of the case study area, this methodology allowed an increased resolution of the DTM, from 30 m/pixel to 10 m/pixel, keeping the same expected vertical error (3 m) as the available SRTM-DTM for the stands with ACCI value lower than 66. Furthermore, those errors can be reduced if a high precision and resolution DTM is available in the area, using UAV imagery only for the calculation of DSM and the consequent CHMs (Lisein et al. 2013). These results obtained here are less promising with increasing canopy cover. Therefore, the use of UAV imagery, and the related methodology presented here, can be recommended for the assessment of canopy height only over open forest or with an intensive visual inspection and manual correction.

6.1.1 Additional description of fire-severity strata

Strata were defined based on the results of the ACCI-based classification, since it demonstrated to be more accurate. The strata description contained on diameter distribution, species, silvicultural class, and regeneration. In all strata, the number of future crop trees per hectare (FCTs/ha) is lower than the 100 FCTs/ha recommended to allow sustainable forest management in Yungas (Grulke et al. 2013). The stratum 'fully stocked' has 93 FCTs/ha, the stratum 'burned' has 65 FCTs/ha, the stratum 'severely burned' has 35 FCTs/ha, and the stratum 'very severely burned' has only 4 FCTs/ha. The low density of FCTs on the stratum 'very severely burned' is compensated by the highest number of established regeneration of valuable species (720 plants/ha). However, this density is slightly lower than the number of seedlings used in a conventional plantation with a planting spacing of 4 m x 3 m (833 trees/ha), where, furthermore, the distribution of the trees would be homogeneous, allowing easy mechanised tending.

The two least degraded strata showed a greater number of FCT, and the expected reverse J-shape on the diameter distribution. It can be concluded that, in principle, these forests would keep delivering mature trees in a middle to long-term perspective. However, the number of FCTs is still below the desired 100 trees/ha. Furthermore, on these strata the density of established regeneration is even lower than in the stratum 'very severely burned.' For the severely burned and very severely burned strata, these results indicate the need for an adaptive stratified rehabilitation plan, such as enrichment planting (EP), in order to increase the future value of the forest. For the strata 'burned' and 'fully stocked,' management of the remaining forest by thinning and a low intensity EP seems to be sufficient.

As far as mature trees are concerned, only in the stratum 'very severely burned' (with 4 trees/ha) the density was lower than the necessary minimum (10 trees/ha) recommended by Grulke et al. (2013), and therefore the potential of present harvesting is low. All other strata had 10 or more mature trees per hectare, meaning that the forest is currently valuable, and important revenues would be acquired if the remaining mature timber is used when rehabilitation takes place. However, extracting mature timber from an already open canopy cover would negatively affect the regeneration, and encourage colonisation by vines and lianas (Wenzel & Hampel 1998; Arturi et al. 2006). Therefore, harvesting should be reserved for 'fully stocked' areas which clearly exceed the benchmark of 10 mature trees/ha, or to areas where trees are cut in order to implement EP.

6.2 Establishing forest management units

In this research, Hot Spot Analysis (Getis-Ord Gi*) has been applied to define meaningful forest management units (FMU) based on RS data. Due to the lack of information to define, a priori, the optimal distance threshold, an approach with four alternative scenarios of analysis was accomplished. The selection of the optimal distance threshold depends, in principle, on the objectives of the study and eventual constraints, such as legislation defining minimal or maximal sizes of areas of intervention, which might be taken into account. In the present study, the criteria to choose the scenarios of analysis were based on experts' recommendations to prefer management units between 10 and 40 hectares. However, in this research, only clusters smaller than five hectares were eliminated, since clusters which are small but nearby an FMU could be manually assigned to them. The results reported that, at the fourth scale of analysis (radius of 357 m), clusters smaller than 10 ha are inexistent, which is in line with experts' advice. The results also revealed a trade-off between increased size and homogeneity of the clusters across the distance threshold gradient. Increasing the distance threshold, the proportion of correctly clustered areas gets closer to the proportion of incorrectly clustered areas. The selection of the most preferred solution should be based on both the feasibility of implementing rehabilitation measures in practice, and the proportion of correctly and incorrectly clustered areas. However, other aspects and criteria could be established in advance, i.e. to limit acceptable percentage of incorrectly-clustered areas on each FMU, regardless of the correctly clustered ones. Also, the distance threshold for which the proportion of correctly and incorrectly clustered areas is equal might be a useful criterion for defining the optimal distance thresholds in operational applications of this methodology. In this research, due to the ease of planning and implementation of rehabilitation measures, the most adequate distance to be used is the largest one (357 m), where the total of correctly clustered areas still exceed the total of incorrectly clustered areas.

The process establishing FMUs should be, on one hand, detailed enough to guarantee the best use of resources, and on the other hand simple enough to apply in practice. Available spatial analysis tools, such as Hot Spot Analysis (Getis-Ord Gi*) from ArcGIS 10.3 environment, can be used for the aggregation of similar and nearby areas. This tool allows for the identification of areas with a concentration of high or low frequencies of an attribute, which is ACCI values in this case. The ACCI is an indicator of forest degradation: the lower the ACCI value of the stand, the more heavily burned it is. The results of the clustering allowed the delineation of FMUs for which specific forest rehabilitation measures can be planned (Fei 2010). However, this approach takes into account the spatial distribution of only one variable of interest for clustering. In contrast, with other optimisation algorithms, such as linear programming, more variables could be taken into consideration (Kašpar et al. 2015), for example wind direction, slopes, and road networks.

The resulting clusters also contain stands with a structure (expressed in ACCI) which is different to the majority (Noce et al. 2016). However, regardless of the distance threshold used for the analysis, the composition of stands for every cluster which is more (distance threshold 178 m) or less (distance threshold 357 m) homogeneous is always known. Therefore, a final manual delineation of the FMU might be advisable to facilitate adaptation of practical management. The final delineation of FMUs can start from both hot and coldspots, and spread into the areas with random distribution of ACCI values. Furthermore, a more detailed delineation, also inside the FMU, should be carried out. It is advised that for the correct management of the hotspots (FMUs designated to forest management), poorly stocked stands within these FMUs should be manually identified for restocking (EP) measures (Keefe 2008; ITTO 2002), and in contrast, for coldspots (FMUs designated to EP), well stocked stands within these FMUs should be left untouched to accomplish their ecological functions.

The weighted ACCI value of the clusters describes the actual ACCI of each management unit as a whole. Finally, based on the degradation level of each FMU (cluster) and its proximity to roads, the selection of areas to be intervened more urgently may be scheduled. The residual commercial timber, and the density of the regeneration of commercial species, are the main concern when defining either the need for intervention or not (Keefe 2008). In FMUs with a high weighted ACCI, the recommendation would be to manage the existing stocks, whereas FMUs with low weighted ACCI would be assigned to EP measures. Clusters with random spatial distribution of ACCI should be further manually delineated in order to implement both EP and management of remaining stocks according to the local situation.

6.2.1 *Landscape connectivity analysis applied to FMUs*

In this research, the establishment of FMUs was conducted using threshold distances set primarily under operational criteria. Therefore, the effect of those established FMUs on landscape connectivity as an important ecological indicator was tested with the software CONEFOR Sensinode 2.2 (CS22). This analysis uses a reference distance of plant (seed) or animal dispersal in order to determine which proportion of the total habitat area can be reached by those organisms of interest (Saura et al. 2011). Since explicit information about seed dispersal for those trees of interest were not found in the literature, two distances were used corresponding to the largest (357 m) and shortest (178 m) distances alternatively used for establishing FMUs. Even though those distances were chosen arbitrarily, they are in the range of seed dispersal by different dispersion types (Vittoz & Engler 2007). For this analysis, only the 'fully stocked' stands were considered, since they were regarded as the ones which contribute most to landscape connectivity.

It is desirable that the greatest area possible of the most important stands for landscape connectivity were clustered as hotspots. This would mean that rehabilitation would be conducted with a low intensity, and most of the native forest cover would be unaffected, and therefore would still offer seeds to neighbouring areas. Larger FMUs (established from the distance threshold of 357 m) benefit a significantly larger area of important stands for landscape connectivity than the results of FMUs with a distance threshold of 178 m. In contrast, different distance thresholds used in the connectivity analysis did not influence the results much. When establishing FMUs with a distance threshold of 178 m, approximately 50 % of the most important stands for landscape connectivity were assigned to hotspots of ACCI values, whereas approximately 70 % when a distance threshold of 357 m was used. It confirms that planning rehabilitation measures based on the hotspots resulted from the distance thresholds of 357 m would not only be favourable due to the size of the acquired FMUs when planning EP, but also for landscape connectivity.

6.3 Enrichment planting

In Argentina, experiences of EP are scarce, and concentrated in the subtropical Selva Paranaense (Montagnini et al. 1997; Montagnini et al. 1998; Montagnini et al. 2006; Dordel et al. 2009; Hennig et al. 2010; Dordel et al. 2011); some cases were reported in Chaco Húmedo (Pérez 2000; Senilliani et al. 2006; Delvalle et al. 2009; Zulle et al. 2015); and only few examples were conducted in Yungas (Mangialavori et al. 2003; Balducci et al. 2009; Del Castillo et al. 2011), where it is not established as a standard silvicultural option yet. Referring to this literature analysis with the identified challenges and promises of EP in Yungas, specific rehabilitation measures can be suggested and planned for Florestoona. The following discussion of EP is divided into two sections: (1) 'EP in Florestoona,' in which the results of the ground inventory of the EP established between 2004 and 2011 are discussed, and (2) 'Understanding the potential and failures of EP in NW Argentina,' in which the practice of EP is discussed in a broader scale, based on literature review, and new concepts of EP to be applied in Florestoona are proposed.

6.3.1 EP in Florestoona

The closest experiment to the one in Florestoona is the one from Del Castillo et al. (2011), who reported the growth of 'toona'(*Toona ciliata*) and 'tipa colorada' (*Pterogyne nitens*) in a 10 year old line EP in Yuto (Salta, Argentina). In their experiment, the native forest was opened in 4 m wide lines spaced every 20 m, and seedlings were planted every 5 m. They reported that 'toona' grows 3.04 cm/y in diameter at breast height (DBH) over the first 10 years, while in Florestoona, the mean annual increment of DBH (DBH-MAI) of group EP (spacing: 4 m x 4 m) with 'toona' was 2.5 cm/y at the age of 11 years. Del Castillo et al. (2011) reported lower growth of 'toona' (DBH-MAI of 1.9 cm/y) at the age of 14 years within an experimental plantation (spacing: 4 m x 4 m) on an open field. This is in accordance to Dordel et al. (2009), who recommended to plant 'toona' under nurse-species, in order to protect them from insolation and frost, in the critical first year of establishment. However, the greatest rates of growth for 'toona' were reported by Mangialavori et al. (2003), who found DBH-MAI of 2.8 and 3.6 cm/y in 5 and 6 year old conventional plantations in Salta, showing the great potential of the species. The least promising results were reported by Delvalle et al. (2009), who tested 'toona' in line planting in the Chaco province, having a DBH-MAI slightly lower than 1.0 cm/y at the age of 17 years.

'Tipa' (*Tipuana tipu*), as a native species alternative, showed in Florestoona an average DBH-MAI of 1.9 and 2.1 cm, at the age of 6 and 7 years, respectively. The planting spacing was 3 m x 3 m, and the planting design was groups and strips, respectively. Those results are similar to the 2.0 cm/y found by Delvalle et al. (2009) in Chaco for 'tipa' in a 17 year old EP area planted in 10 m wide strips. However, Del Castillo et al. (2011) reported DBH-MAI lower than 1 cm/y for 'tipa colorada' (close species to 'tipa'), in an 8 year old line EP.

EP is often criticised due to the high need for tending. To compensate the related costs, fast growth and early harvesting would be desirable to shorten the time until the investment is returned (Montagnini et al. 1997; Loewe M. et al. 2013). Grulke et al. (2013) recommended using the combination of at least four species in order to reduce the risk of failure and to diversify the production, and to plant at least 50 % of the area with rapid growth species. This can be accomplished by mixing fast growth timber species in the EP area, or by the association of non-timber species, such as *Ilex paraguariensis* (Montagnini et al. 2006). However, in Florestoona, the combination of species showed a negative effect on growth in comparison with monospecific EP: 'toona,' at the age of 11, reported 2.5 cm /y of DBH-MAI, when planted in monospecific EP, and 1.9 cm/y when it is mixed with 'paraíso.' 'Paraíso' grows between 3.7 and 4 cm/y when planted monospecific, whereas it grows 2.3 cm/y when it is associated with 'tipa,' and only between 1.3 and 2.5 cm/y when it is associated with 'toona.' 'Tipa' also reported lower growth in DBH when planted mixed with 'paraíso.'

Mixed species EP could also play a role in protecting light-sensitive species. Dordel et al. (2009) claimed that 'toona' suffers a great rate of mortality in open plantations, since it needs shelter in the first two years (Dordel et al. 2009). These authors reported reduced mortality rate and the increased growth of 'toona' by planting it under six year old *Grevillea robusta* A. Cunn. (Proteaceae) trees as a nurse-tree species. Dordel et al. (2011) confirmed those results when they found that the photosynthetic capacity of 'toona' is linked to nutrient availability, which are increased by nurse-trees, since they provide abundant higher soil potassium (K) and phosphorous (P). However, those experiments were conducted in Misiones province (North-eastern Argentina), and cannot be extrapolated to other soil and climate conditions. Hennig et al. (2010) assessed 'paraíso' in mixed-species plantations with *G. robusta* in the south of Misiones province. At the age of 4 years, 'paraíso' trees showed a DBH of 11.8 cm (MAI of 2.95 cm/y), which is lower compared to the monospecific EP in Florestoona, but higher when planted in association with 'toona.' However, the authors suggested that this design could contribute to reducing the risk of phytoplasma (a known and spreading disease of 'paraíso' in Argentina [Gomez et al. 1996]), since it would be harder for disease carriers to find 'paraíso' trees.

In Florestoona, in opposition from the results of Ådjers et al. (1994), line orientation did not show any effect on the growth of the assessed species. Line orientation plays a more important role when sunlight is limited, which is not a problem in the (sub)tropics, and can be overcome with wider planting spacing (Ådjers et al. 1994). Therefore, when sunlight is not limited, lines should be defined by the terrain conditions, in order to facilitate operations and reduce erosion.

The design effect (single line, strips or groups) could not be isolated from species composition due to the low number of measured samples (or inexistent in case of line planting) and the lack of experimental design while establishing the EP in Florestoona. However, based on former experiences of Florestoona's forest managers, single line EP should be completely excluded, since they require high effort (and cost) for tending, and show high mortality and low growth rates.

Beside the establishment, maintenance is crucial for the long-term success of EP. Schulze (2008) mentioned that the high cost of maintenance of the EP could be the cause of the low acceptance of the concept in practice. Therefore, the designs of wide strips and groups seem to be most efficient, and with the lowest cost of implementation since the competition of neighbouring trees and the cost of tending are reduced due to the decreasing edge effect. Even though the reported results for strips and group EP in Florestoona are promising, it must be considered that bigger areas could further reduce the proportion of the area negatively affected by the edge effect on the border lines. In the inventory of EP in Florestoona, trees on border lines were excluded from the measurements, because the lower size of the trees was evident. To include them would have negatively affected the calculated growth potential of the EP species. The border line includes close to 60 and 80 % of all trees when planted in strip EP with 7 and 5 lines, respectively, and of approximately 50 % of all trees, if a group EP design of 45 m x 40 m was applied.

Under the constraint that the reported average growth rate would be constant in time, the rotation of the three species can be calculated for a target DBH of 40 cm. Assessing the final density from the EP area with 'paraíso' (reference block: ParaisoThinned2011), 23 % of the originally planted trees would be harvested at the end of the rotation. This means that 190 trees/ha are to be harvested after 10 years. Using this harvesting rate as a reference for 'toona' (reference Block: Toona2004), 143 trees/ha are to be harvested after 15 years from plantation, and for 'tipa' (reference block: Tipa2009) 255 trees/ha are to be harvested after 20 years.

6.3.2 Understanding the potential and failures of EP in NW Argentina

Even though EP has been studied and implemented in the last 60 years (Dawkins 1961; Lamprecht 1990) for restocking overexploited forests, the experiments are few, and most of them report growth below expectations. Furthermore, there is a lack of information about the performance of EP experiments. Many of the cited contributions are grey literature or conference papers, and most of the reported experiments (as in Florestoona) were established on a trial and error basis, and without an adequate statistical design. Furthermore, the diverse EP designs, plantation spacing, species, and site conditions of the experiments make it difficult to identify and compare the causes of the failure.

Between the technical factors limiting the implementation of EP in the region, three key aspects are important to consider: selection of species, design, and size of EP compartments. With regard to species selection, suitable candidates should meet some requirements, such as rapid height growth, good natural stem form, and production of high value timber, among others (ITTO 2002). Di Marco (2014) and INCOTEDES (2014) recommended several species for EP (including 'tipa blanca,' 'paraíso,' and 'toona'), but without mentioning the criteria used for the selection of those species. Likely, they were selected due to the high value of timber from those species. Those species were already used in Florestoona, and seem to be adequate for further use, since, as previously discussed, they might also allow shorter rotation periods in comparison with the ones reported by Lozada et al. (2013) and Noguera et al. (2006), who found rotation periods of between 40 and 100 years for several species tested in the Venezuelan Guayana.

The high cost of tending, especially in line EP, is a recurrent problem mentioned in all cited publications, and can be identified as the main reason of its so far limited implementation. Furthermore, most of the line EP experiments limit the tending to narrow areas beside the planting line, so the competition with surrounding vegetation is not completely eliminated. Therefore, to avoid this, the tending should be extended to bigger areas, as recommended by Lamprecht (1990). The author proposed that, at 1 m at both sides of the axis of plantation, all vegetation must be removed; up to 5 m to each side all brushes, and trees up to 2 m high must be removed. The remaining strip of 10 m width should be left with natural forest, meaning that 50 % of the area is modified.

However, there is scepticism to implement this intensive tending, since for some authors it would actually be considered an overexploitation (mining use) of the forest (Lozada et al. 2013).

In many cases, EP has been implemented among degraded forests in a schematic pattern (Stroessner 1978; Montagnini et al. 1997; Noguera et al. 2006; Rodriguez et al. 2011; Lozada et al. 2013; Di Marco 2014). However, according to Vicent (2004), it seems to be more effective to first identify the most degraded areas in order to know where it is meaningful to allocate the EP effort. As a consequence, the impact on the natural ecosystem by introducing EP might be minimised if EP is conducted only on specially selected areas of about one to five hectares (Vicent 2004), and it would reduce the pressure of cutting on the areas designated to permanent native forest cover.

From the literature review, it can be concluded that, based on a detailed map of forest degradation, and having defined the areas for the implementation of EP, it is advisable to introduce also bigger plots of EP, if they are adapted to the spatial pattern of degradation. The advantages would be: (1) the efforts are concentrated on heavily degraded areas, (2) the costs of the tending are reduced, (3) the minimum levels of environmental protection are respected, and (4) the pressure on the surrounding forest is also reduced, since the EP areas would provide timber at a lower cost.

6.3.2.1 New concepts of EP for Florestoona

An effective rehabilitation of degraded forests requires the establishment of FMUs in order to concentrate the activities based on similarities in forest structure, and make EP interventions economically feasible. FMU sizes between 10 and 40 ha, depending on the variation in forest structure and terrain, are recommended by practitioners (pers. comm. with forest managers). However, the maximum area to be planted is also linked to ecological and legal factors. For instance, based on forest land use planning according to national law 26331, Florestoona belongs to the group of areas with medium value of conservation, where the forest cover must be kept. In this area, particular regulations are given for properties of areas larger than 1,000 ha, and with slope of terrain between 7 % and 15 %. For these areas, the decree 2211/2010 requires a minimum of 50 % of the area to be designated to permanent native forest cover. In 40 % of the area, land use change is allowed when its goal is to remain as forest use (e.g. silvopastoral systems and under canopy agroforestry). The modified areas should not exceed 120 ha. At their borders, protective forest strips of natural forest must be kept intact for protecting fauna and erosion functions. Those strips must be 100 m wide and oriented in east-west and north-south directions. Additionally, every 4,000 m in both directions, a wider strip (240 m) must be kept.

As a consequence of the findings previously discussed, in Florestoona, EP is recommended for all degraded forest strata in order to rehabilitate forest cover, productivity, and protective functions. However, EP should not cover more than 50 % of the cadastral area in order to follow the requirements of law 26,331, and the recommendations of Lamprecht (1990), in terms of total affected area. As recommended by Vicent (2004), EP efforts should be allocated where the forest is most degraded, and not just schematic among the whole forest.

A first stage might be completed with fast growing species (mostly exotic, such as 'toona' and 'paraíso'), and the second stage might be a combination of fast growing species and exclusively native species in the understory. In the first stage, EP with exotic species would be repeated for as many cutting periods as necessary until the restocking of the permanent native cover strips is guaranteed, before starting the second stage (EP with native species).

Following are listed three adaptive measures, exampling possible strategies to be applied in Florestoona for different degrees of degradation:

- In FMUs established from coldspots, and with weighted ACCI value below 33, EP would cover up to 75 % of the area. Strips of permanent native forest cover with a minimum width of 100 m would ideally separate every 300 m of EP area. However, those distances should be flexible in order to optimise their location in accordance to the spatial distribution of intact ('fully stocked') stands. Since these FMUs are heavily degraded, surrounding strips of native forest cover may be hard to find. In those cases, it is recommended to complete those strips of EP with native species.

- In FMU where the distribution of the degradation is regarded as random, and with weighted ACCI value between 33 and 40, EP would be practiced in up to 50 % of the FMU. Native forest strips with a minimum width of 200 m would separate areas of EP with 200 m width. This pattern can be modified to optimise the location in accordance with the spatial distribution of intact (fully stocked) stands.
- In FMU formed from hotspots, and with weighted ACCI value between 40 and 66, EP would be practiced in only up to 25 % of the FMU. EP strips of 100 m width would optimally be separated by 300 m of native forest. This can be modified to optimise their location in accordance to the neighbouring, intact (fully stocked) stands.

A strip length of 500 m would result in enrichment compartments of 15, 10, and 5 ha, respectively, for each of the three categories presented. However, alterations of the length can be applied if it facilitates the operations, but the maximum area of 15, 10, and 5 ha should not be exceeded. In all native forest strips, silvicultural measures must be applied with liberation thinning, pruning, and selective logging to facilitate the growth of the future crop trees. The orientation of the permanent native forest strips should be flexible in order to adapt it to the slope orientation, when the inclination is greater than 10 %.

The selection of the species to be planted in monospecific plantations, based on the local experience, are 'paraíso' and 'toona.' In cases where the heavily degraded forest is extended in a greater area than the maximum recommended for EP (15, 10, or 5 ha for coldspots, random areas, and hotspots, respectively), the native species 'tipa' is recommended for EP in the exceeding area.

6.4 Example of implementation of rehabilitation measures in Florestoona

In this chapter, the approach presented so far to plan rehabilitation measures in Florestoona is described in an example case. The example area contains 734.7 ha, where the types of FMU and their compartments are mapped in detail in order to define adapted rehabilitation measures, including stand management with EP and the possible extraction of wood. This area was chosen because the three situations of clustering are present and evenly distribuited with a concentration of low (coldspot, 239.2 ha), high (hotspot, 253.3 ha), and random distribution (242.2 ha) of ACCI values. Figure 50 reports the respective mapped FMUs based on the threshold distance of 357 m on the Hot Spot Analysis (Getis- Ord Gi*).

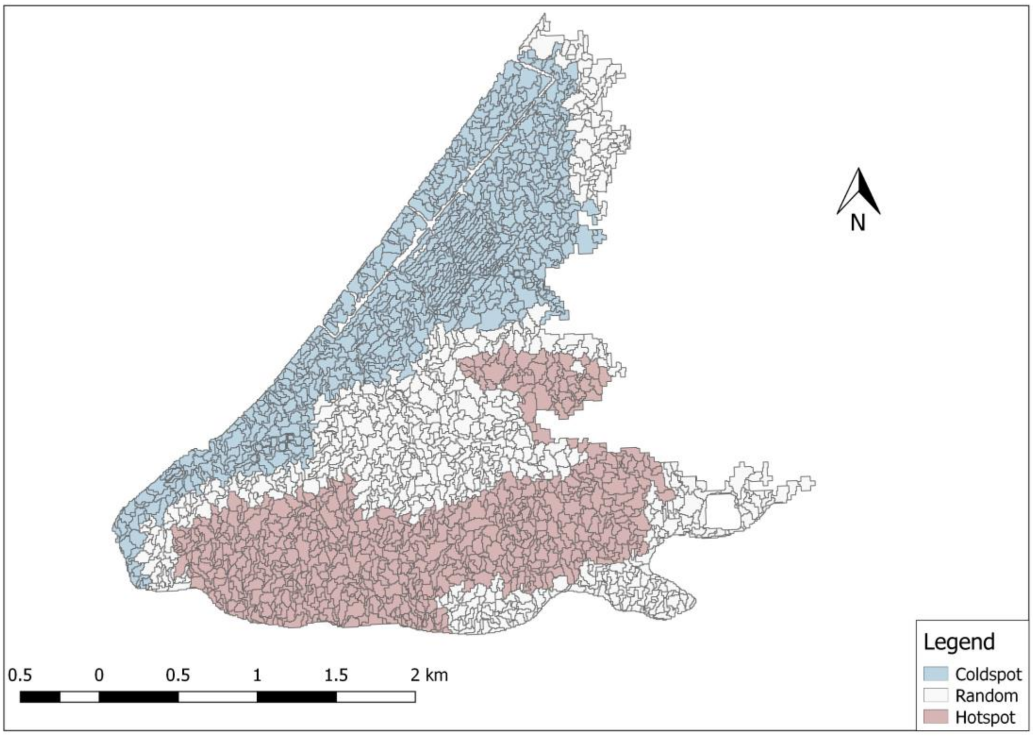


Figure 50: Map of hotspot, coldspot and not clustered ACCI values of an example area of 734.7 ha, where adaptive rehabilitation is planned accordingly to the FMU defined from cluster analysis and their stand's composition of degradation strata acquired from the previous image classification.

After FMU were delineated during cluster analysis, their borders were manually modified in order to simplify the planned operations. Compartments inside each FMU were delineated manually, with the constraints of maximum area to be enriched per FMU type (75 %, 50 %, and 25%, respectively, for coldspot, random, and hotspot

FMUs), maximum area of compartment (15, 10, and 5 ha, respectively, for coldspot, random, and hotspot FMUs), and trying to maximise the homogeneity of degradation inside the unit. This information is available from the ACCI-based image classification into four fire-severity strata (Figure 51), which was overlaid to the FMUs map in order to define compartments inside FMUs.

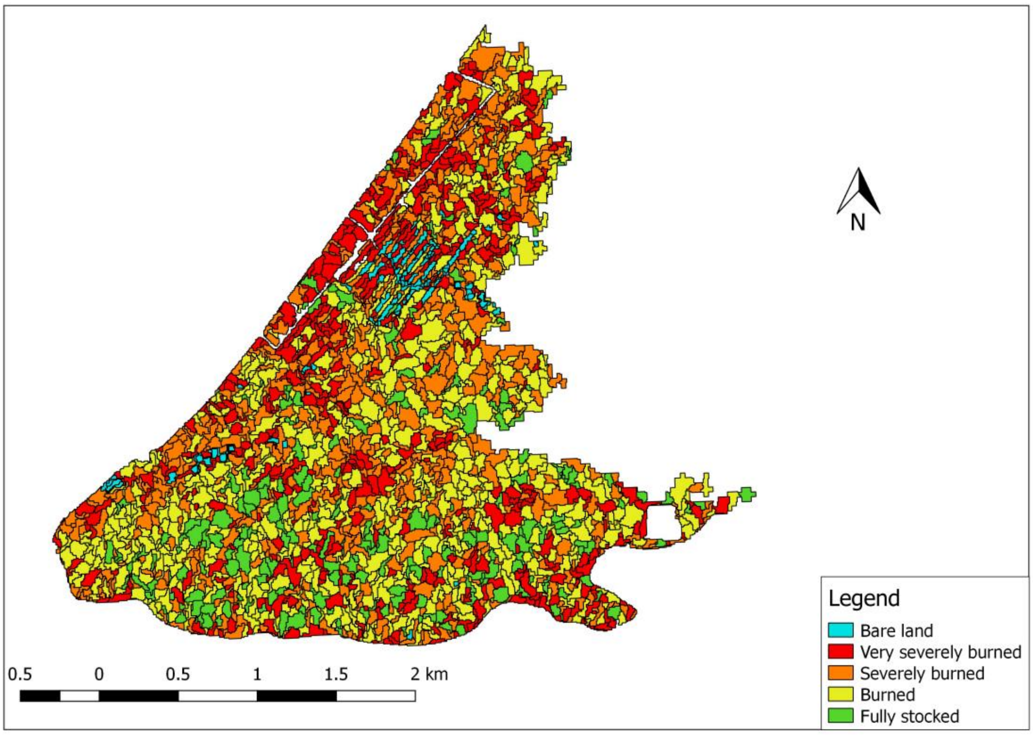


Figure 51: Map of degradation severity (very severely burned, severely burned, burned, fully stocked, and bare land) for an example area of 734.7 ha, where EP for rehabilitation is differently planned according to the FMU defined from cluster analysis and local economical degradation severity from image classification.

Figure 52 shows the first manual delineation of three types of compartments, which follow the rules and recommendations presented in the chapter 'New concepts of EP for Florestoona.' Namely, (1) EP with exotic species, (2) EP with native species, and (3) permanent native forest cover. Thereafter, a second map was created manually, where compartment edges were simplified in order to reduce the edge effect and facilitate operations (Figure 53).

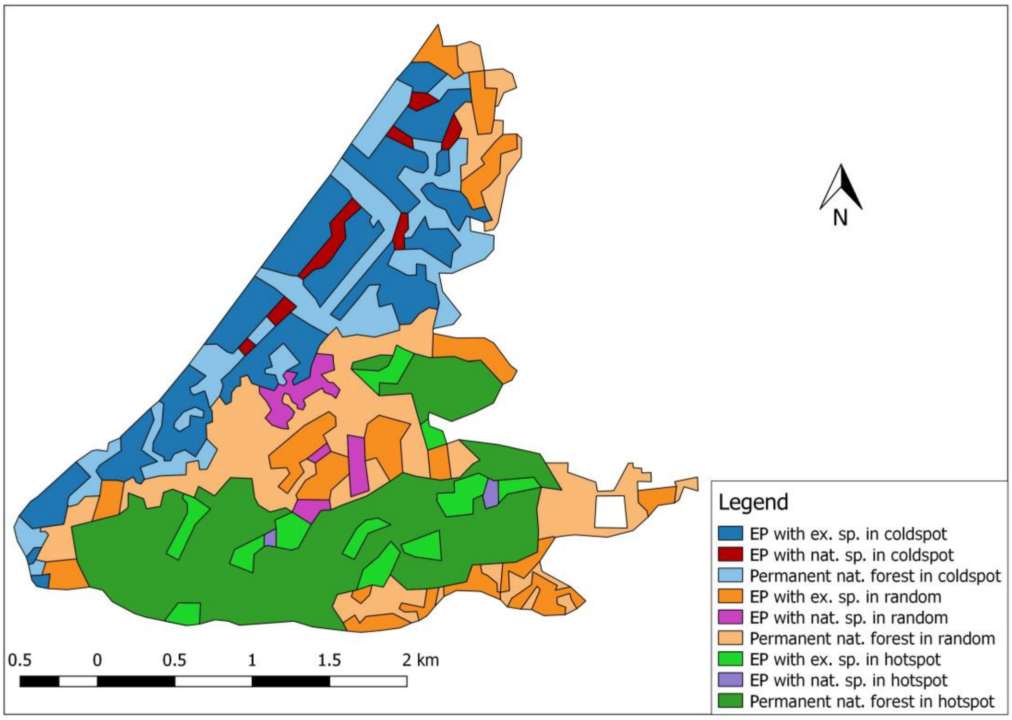


Figure 52: Map of a first manual delineation of compartments maximizing their homogeneity based on the fire-severity strata. Coldspots, hotspots, and random distributed areas with recommended measures are mapped separately

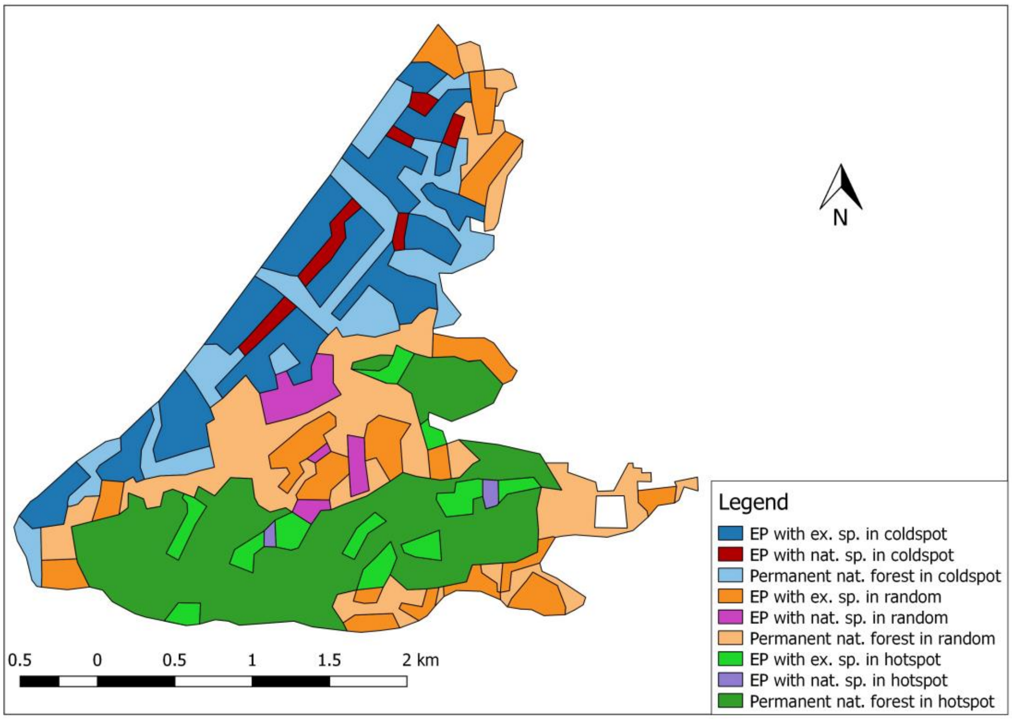


Figure 53: Map of a modified delineation of EP and native forest compartments, where the borders of compartments are adjusted in order to simplify operations. Coldspots, hotspots, and randomly distributed areas with recommended measures are mapped separately

Table 30 reports total area per FMU and partial area in hectare and percentage designated to each of the compartment types from Figure 53. In this table, one can observe that the percentage of EP for each of the FMUs is lower than the threshold of maximum area to be enriched per FMU type. In the FMU 'coldspot,' the total area to be enriched reaches 62 % of the unit (the sum of 55.4 % from EP with fast growth exotic species and 6.6 % of EP with native species), whereas the maximum recommended was 75 %. The same situation is presented for the FMUs 'random' and 'hotspot,' where the planning reaches 42.6 and 16.7 %, while the maximum areas recommended for conversion to EP were 50 % and 25 %, respectively.

Table 30: Total area expressed in hectare and percentage (in brackets) per compartment type (EP with exotic species, EP with native species, and permanent native forest cover) and FMU type on the selected example area (total size of 734.7 ha; See Figure 53).

FMU type	Total area	EP with exotic species	EP with native species	Permanent native forest
Coldspot	239. 2	132.4 (55.4)	15.8 (6.6)	90.9 (38.0)
Random	242.2	88.9 (35.1)	19.1 (7.5)	145. 3 (57.4)
Hotspot	253.3	37.4 (15.4)	3.0 (1.3)	201.8 (83.3)

Table 31 shows the areas (in hectares) of each of the three FMUs planned for EP with exotic species, and Table 32, for EP with native species. For all FMU types, less than 25 % of the area designated for EP with exotic species originated from 'fully stocked' or 'burned' degradation strata. In the case of EP with native species, this percentage is 27.2 for the FMU 'random.' That means that most of the enriched area (approximately 75 %) originate from stands with an ACCI value lower than 33. Referring to the example area of 734.7 ha, 40 % (296.6 ha) is planned to be enriched (258.7 ha with exotic species and 37.9 ha with native species).

Table 31: Areas planned to be rehabilitated by EP with fast growth species ('toona' and 'paraíso') in the FMU formed from hotspot, coldspot, and random distribution of ACCI values, from the selected example area.

FMU type	**Fully stocked**	**Burned**	**Severely burned**	**Very severely burned**	**Bare land**	**Total**
Coldspot	1.5 (1.1)	14.1 (10.7)	56.9 (43.0)	50.4 (38.1)	9.5 (7.2)	132,4
Random	3.9 (4.4)	17.4 (19.6)	39.4 (44.3)	27.7 (31.2)	0.5 (0.5)	88,9
Hotspot	2.2 (6.0)	5.3 (14.2)	17.0 (45.6)	12.8 (34.2)	0 (0)	37,4

Table 32: Areas planned to be rehabilitated by EP with native trees ('tipa') in the FMU formed from hotspot, coldspot, and random distribution of ACCI values from the selected example area.

FMU type	Fully stocked	Burned	Severely burned	Very severely burned	Bare land	Total
Coldspot	0,2 (1.5)	3,6 (22.5)	4,3 (26.9)	7,0 (44.4)	0,7 (4.7)	15,8
Random	0,1 (0.4)	5,1 (26.8)	9,4 (49.3)	4,5 (23.5)	0.0 (0.0)	19,1
Hotspot	0,2 (7.2)	0,6 (19.4)	1,5 (49.5)	0,7 (23.9)	0.0 (0.0)	3,0

Table 33 shows that the areas designated to be treated as permanent native forest strips (no intervention/closure) or conventional forest management (thinning and pruning) mainly originated from stands classified as 'fully stocked' and 'burned,' based on the ACCI-based image classification. Consequently, these areas are composed of low percentage of stands classified as 'very severely burned,' 'severely burned,' or 'bare land.' The least homogeneous case is the 'coldspot' FMU, where 39.4 % of those areas were previously classified as 'severely burned,' 'very severely burned,' or 'bare land.'

Table 33: Areas planned to be restored by forest management (closure, thinning, and pruning) in the FMU formed from hotspot, coldspot, and random distribution of ACCI values from the selected example area.

Cluster	Fully stocked	Burned	Severely burned	Very severely burned	Bare land	Total
Coldspot	6,4 (7.0)	48,8 (53.6)	19,3 (21.2)	12,5 (13.8)	3,9 (4.3)	90,9
Random	19,2 (13.2)	81,9 (56.3)	31,6 (21.8)	12,3 (8.5)	0,3 (0.2)	145,3
Hotspot	51,2 (25.4)	96,98 (48.0)	34,8 (17.2)	18,8 (9.3)	0,1 (0.0)	201,8

Since the terrain in compartments designated to EP must be completely free from single, or groups of, trees in order to give light to the EP plansts and to facilitate operations, the volume of good quality timber, which could be potentially harvested to prepare the operation, can be calculated based on the inventory results. Per hectare of 'fully stocked,' 'burned,' 'severely burned,' and 'very severely burned' forest, 14.6, 5.4, 3.9, and 1.9 m^3/ha of valuable timber can be harvested, respectively. That means that a total of 1064 m^3 will be harvested in the example area. It corresponds to 467 m^3 (3.15 m^3/ha) of valuable timber harvested from EP over coldspot, 432 m^3 (4 m^3/ha) from the random, and 166 m³ (4.1 m³/ha) from the hotspot FMUs. The revenues from the timber sales could financially support the cost for establishing EP.

6.4.1 *Validation of landscape connectivity*

Finally, the environmental impacts of these planned rehabilitation measures were assessed by conducting a connectivity analysis for the example area, and analysing the proportion of the most important 'fully stocked' areas by their contribution to the landscape connectivity, which is compromised in EP measures. Consequently, the proportion that is effectively part of permanent native forest cover can be derived. From the 48 ha of 'fully stocked' forests, 50 % were classified as most important for their contribution to landscape connectivity; 46 ha are assigned to be part of strips of permanent native forest or conventional forest management. The reason is obvious: high values of integral index of connectivity (IIC) are related to the stands which contributed most to the connectivity (big areas of 'fully stocked' forest close to each other), and those areas are usually related to hotspots of ACCI values, where also the lowest percentage of EP is planned.

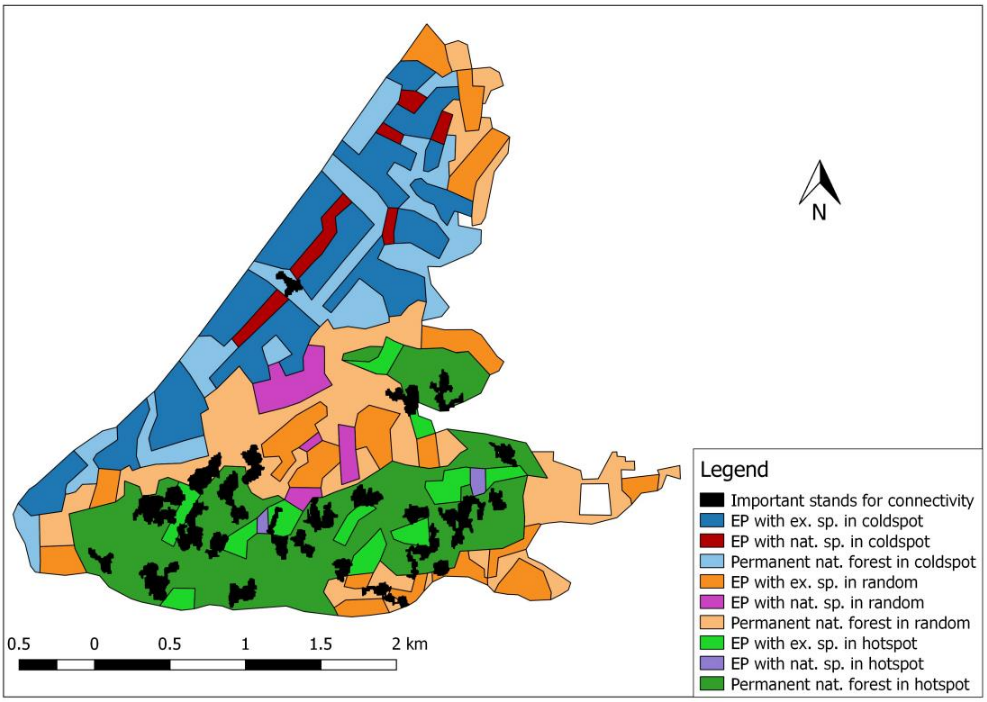


Figure 54: Validation of the location of EP compartments based on the identification of the most important stands of native forest by their contribution to landscape connectivity, identified with the integral index of connectivity (IIC) in the software CONEFOR Sensinode 2.2.

7 Conclusions

7.1 Image classification supported with UAV imagery

The formulation of the adjusted canopy cover index (ACCI) derived from forest structure variables (canopy cover [CC] and tree heights), and its correlation to forest stock (basal area [BA]), allowed to accurately classify forest degradation. CC and tree heights were derived from the analysis of partial cover unmanned aerial vehicle (UAV) optical imagery, whereas BA was derived from measurements on the ground. A three step area-based approach was chosen, where a certain number of sample plots is still necessary to establish the correlations, and additional image plots can be measured on UAV imagery to train and improve the classification. As a result of the combination of ground inventory data, partial cover UAV imagery, and wall-to-wall satellite images, an accurate assessment and mapping of a heterogeneously degraded forest on a medium scale (approximately 4,000 ha), was achieved. Since no precise digital terrain model (DTM) was available, DTM was calculated exclusively from optical UAV images.

When calculating UAV image derived DTM (also digital surface models [DSMs] and canopy height models [CHMs]), the source point cloud lacks data related to the terrain, and most of the lowest acquired data in the point cloud are actually related to low canopy. Therefore, tree heights are underestimated, with a root mean squared error (RMSE) ranging from 2.8 to 8.3 m, having the greatest error over close canopy forests (ACCI larger than 66). From the two DTM resolutions (5 m and 10 m) tested, the best accuracy was achieved using the largest pixel size, since it is less sensitive to small areas with dense canopy. Since the available DTM in Argentina has a 30 m/pixel resolution, it can be concluded that this approach can be recommended where no high resolution DTMs are available, and the acquisition of airborne laser scanning (ALS) data is limited by the project budget or available technology.

The results of this dissertation show a remarkable contribution of partial cover UAV imagery-derived metrics to reduce stratified estimation error in an area-based inventory, in comparison with the traditional approach of using only satellite imagery and ground plots. This approach allowed us to accurately classify a wall-to-wall satellite image into four fire-severity strata over large areas, requiring a relatively low number of ground plots (77 plots over 2,944 ha). Even when the overall classification error was not improved, the advantage of this approach was to reduce the number of outliers in the classification (stands classified into a very different strata). That was the case of land covers with similar spectral response, but very different stocks and structure, such as dense canopy forest and areas colonised with vines or shrubs. A conventional area-based inventory would have required an additional 45 ground plots to achieve a target stratified estimation error (BA-based) of 20%, whereas in the conducted case study, the target error was achieved with an additional 20 image plots over partial cover UAV imagery.

Further analysis of the acquired strata showed that the fire affected mainly small trees, producing a negative effect on the economic value of the forest in the medium and long term, due to the low number of future crop trees (FCTs) left on the most degraded stands. Therefore, EP should be accomplished with rapid growth species in order to rapidly cover the gap of trees between 10 and 20 cm diameter at breast height (DBH).

7.2 Establishing forest management units

The tool 'Hot Spot Analysis (Getis-Ord Gi*)' from the environment ArcGIS can be used for the data-supported automated formation of forest management units (FMUs) as a first draft, when related spatial information of the forest is available. In the case study, the input data was a map of stands classified into fire-severity strata, according to their structure (using ACCI as a metric), derived from the classification of a SPOT6 image supported with UAV imagery. The tool allowed to cluster areas of similar structure and adequate size, where rehabilitation measures can be put in place. The tool demonstrated to significantly aggregate between 30.7 % (178 m threshold distance) to 60.8 %

(357 m threshold distance) of the area into either cold or hotspots. The trade-off between cluster size and their homogeneity can be quantified for alternative target sizes of FMUs. This allows choosing threshold distances for the clustering which are adequate to the planning of management activity. It is suggested to choose the distance threshold to establish FMUs to plan adaptive rehabilitation measures, based on the size of the resulting cluster. Then the larger the cluster (accounted as a FMU), the more desirable it is, as long as the total of correctly clustered areas exceeds the total of incorrectly clustered areas. In this case, this was achieved with the distance threshold of 357 m. As an alternative, a certain size of incorrectly clustered areas could be set as a threshold for the selection of the appropriate neighbouring radius distance when establishing FMUs.

Depending on the heterogeneity of the forest area, i.e. the difference in structure between neighbouring stands, not all stands can be clustered successfully on a significant level, leaving 'randomly distributed areas.' These can be manually included in adjacent clusters, or managed as separate FMUs with mixed-management approaches. Furthermore, the ACCI-based 'automatic' establishment of FMUs should be critically reviewed and manually adapted with regard to technical aspects like terrain, shape of the stands to be managed, and road access. The presented clustering approach has its limitations when complex ecosystems are analysed, because only one single variable (ACCI) is used as attribute for clusterisation.

The results of the evaluation of the ecological impact of implementing enrichment planting (EP), based on landscape connectivity analysis, showed that approximately 70 % of the most important 'fully stocked' stands will be managed as part of permanent native forest cover compartments (resulting from hotspots of high ACCI values). Those results were obtained based on the map of FMUs established with a neighbouring radius distance of 357 m. If the FMU map of a neighbouring radius distance of 178 m were considered, 50 % of the most important 'fully stocked' stands would be compromised on coldspot (intensive forest management) or random distribution areas (medium intensity forest management). Those results support the selection of the distance threshold of 357 m to run the hotspot analysis, since it also assures the protection of the majority of the most important 'fully stocked' stands, which are important for connectivity.

7.3 Enrichment planting

The results from this dissertation show that the exotic species 'paraíso' (*Melia azedarach* L.; Meliaceae) and 'toona' (*Toona ciliata* M. Roem., Meliaceae), and the native species 'tipa' (or 'tipla balnaca,' *Tipuana tipu* Kuntze, Fabaceae) have potential for EP in the Yungas when they are planted in monospecific compartments. At the ages they were measured (5, 6, and 11 years), they showed a mean annual incremental DBH of 4.0, 2.1, and 2.5 cm, respectively. Even though the measured trees are too young to decide on the adequate rotation period for the species, it would be expected that the rotation period based on a DBH of 40 cm would be reached after 15 years for 'toona,' 20 years for 'tipa,' and 10 years for 'paraíso.' However, due to the edge effects, those results are valid only for the trees located in the core of the EP areas, where the measured plots were located. Due to the small areas of the EP blocks established so far in Florestoona, the two border lines occupy between 50 % and 80 % of the enriched areas, what has negative effects on the average growth of the EP blocks.

The combination of species in the same EP blocks established in Florestoona reported negative results for all tested species, whereas line orientation did not report any effect on growth, and EP design (strips and groups) could not be isolated from species effect.

The literature review revealed a big gap of information and lack of experiences of EP in Yungas. Based on the current application of EP, it can be concluded that, at present, many homogeneous small interventions, mostly as single line EP along the forest, are dominating, even if maintenance is expensive and the results in growth are under expectations. Up to now, there is scepticism about the implementation of EP in big areas, since they are regarded as 'mining activity,' affecting negatively on the remaining forest structure. However, new approaches of knowledge-based adaptive planning, as presented in this dissertation, allow to identify, more precisely, target areas according to their degree of degradation, so that rehabilitation measures can be adjusted in design, size, and spatial distribution without compromising the remaining forest.

7.4 Future studies

Further research should concentrate on the cost-efficiency of the area-based inventory alternatives presented (two and three step approaches) to justify or reject the use of partial cover UAV imagery at different scales and target errors. Multi-temporal analysis, where the precision of the image-derived DTM from forest areas affected by mixed-severity fires is evaluated at different stages of vine colonisation, is another topic to consider in further studies. Also, the usefulness of the presented concept should be tested for forest degraded by different causes form fires, i.e. overexploitation or shifting cultivation.

Advanced approaches to automatically establish FMUs should be developed in order to include more than one forest structure variable (such as ACCI in this case), and possibly other terrain and site attributes.

Furthermore, it is recommended to study the growth of native species under cover from 'toona' and paraíso' in order to test the conversion from EP to native forest after the forest is again fully stocked.

8 Annex

8.1 Annex 1: minimum diameter for logging table. Provincial decree 15142/1960.

Local name	**Latin name**	**Minimum log diameter (cm)**
Afata o Peteribí	*Cordia tricotoma*	40
Arca, Visco o Viscote	*Acacia visco*	30
Aliso del Cerro	*Alnus jorullensis var. Spachii*	30
Algarrobo blanco	*Prosopis alba*	40
Algarrobo negro	*Prosopis nigra*	35
Azota caballo	*Luechea divaricata*	30
Cebiles colorados o Curupay moro	*Piptadenia macrocarpa*	30
Cedros salteño y coya	*Cederla balansae y C. lilloi*	40
Espinillo, Palo cascarudo	*Pithecellobium scalare*	30
Guyacán	*Caesalpinia paraguariensis*	30
Horco cebil	*Piptadenia excelsa*	30
Horco quebracho	*Schinopsis haenkeana*	30
Lanza blanca	*Patagonula americana*	25
Lapacho rosado y amarillo	*Tabebuia avellanedae, T. Lapacho*	40
Laurel blanco, Peludo de la falda	*Ocotea puberula, Phoebe porfiria*	35
Mora amarilla	*Chlrophora tinctoria*	40
Mistol	*Zizyphus mistol*	25
Nogal criollo	*Juglans australis*	40
Pacará	*Enterolobium contortisiliquum*	40
Palma negra	*Copernicia alba*	07
Palo amarillo	*Phyllostylom rhamnoides*	30
Palo blanco	*Calycophylom multiflorum*	30
Palo barroso	*Blepharocaly gigantea*	30
Palo santo	*Bulnesia sarmientoi*	35
Pino del cerro	*Podocarpus parlatorei*	30
Quebracho colorado santiagueño	*Schinopsis lorentzii*	30
Quebracho blanco	*Aspidosperma quebracho blanco*	30
Quina colorada	*Miroxylon peruiferum*	40
Quina blanca	*Lanchocarpus lillloi*	35
Roble	*Amburana caerensis*	60
Sauce criollo o colorado	*Salix humboldtiana*	30
Ceibo	*Erythrina falcata*	30
Tarco o Jacarandá	*Jacaranda mimosifolia*	30
Tipa amarilla	*Cascaronia astragalina*	30
Tipa colorada	*Pterogyne nitens*	40
Tipa blanca	*Tipuana tipu*	35
Virarú	*Ruprechtia polystachya*	30

8.2 Annex 2: inventory protocol

Fulfil the inventory field sheet (Figure 56) with the following data:

- Date.
- Starting time: Set the starting time when the central point of the plot is reached.
- Coordinates: Special protocol for Trimble Geo XH 6000.
- Navigate to the waypoint, to a precision under 1m.
- Go to data- file name: use the default one.
- Confirm antenna type to 0 m.
- Chose file type: Point-generic.
- Comment: given name by inventory plan.
- Start log: In parallel start alarm in mobile to 5 minutes.
- Five minutes later: Stop logging and save file.
- Plot id: The plot number is the same that the one is charged in the GPS and shown in the map.
- Forest type:
  - Based on stratification: What is the expected plot strata?
  - Based on observation: What is the strata in which the plot appears to fit better?
- Inner plot: Size of the radius of the inner plot: radius of 9.77 m. If the number of trees is lower than 8, the radius is changed to 17.84 m. Trees from 10 cm, and lower than 30 cm, DBH were measured.

  Outer plot: Size of the radius of the outer plot: 17.84 m for all the strata. All trees measured have a DBH from 30 cm.
- Team: Name all the persons who are part of the field work for this plot.
- Picture: take a picture, and note its storage name on the direction of the shot from the centre point of the plot.
- Slope: Estimate slope with vertex, and note the direction of the slope up.
- Weather conditions: approx. cloud coverage, approx. temperature, windy or not.
- Species: local name are listed in Table 34.

Table 34: Species and local name of the trees expected to be found in Florestoona

Local name	**Species name**	**Local name**	**Species name**
Afata	*Cordia trichotoma*	Pacará	*Enterolobium cortor-tisiliquum*
Aguay	*Chysophyllum gono-carpum*	Palo amarillo	*Phyllostilon rham-noides*
Arca	*Aacia visco*	Palo blanco	*Calycophyllum multi-florum*
Cascarón	*Cascaronia atragalina*	Quina blanca	*Lonchocarpus lilloi*
Cebil moro	*Anadenanthera colu-brine*	Quina colorada	*Myroxylon peru-iferum*
Cedro Orán	*Cedrela balansae*	Roble	*Amburana cearnsis*
Horco cebil	*Parapitadenia excels*	San Antonio	*Myrsine laetevirens*
Lanza amarilla	*Terminalia triflora*	Tarco	*Jacaranda mimosifolia*
Lanza blanca	*Patagonula americana*	Tipa blanca	*Tiopuana tipu*
Lapacho	*Tabebuia impetiginosa*	Tipa colorada	*Pterogyne nitens*
Laurel blanco	*Ocotea puberula*	Urundel	*Astronium urundeuva*
Mora	*Chlorophora tinctoria*	Virarú	*Repretchia laxiflora*
Mato	*Eugenia mato*	Guayabil	*Saccellium lanceola-tum*
Lanza	*Phyllostylon rham-noides*	Duraznillo	*Ruprechtia apetala*
Pata	*Agonandra excelsa*	Coronillo	*Gleditsia amorphoides*
Espinillo	*Pithecellobium scalare*	Lecheron	*Sebastiania brasili-ensis*
Palo borracho	*Ceiba chodatii*	Quebrachillo	*Acanthosyris spi-nescens*
Molle	*Blepharocalix salicifo-lius*		

- DBH. Diameter at breast height. Must be measured with diameter tape at 1.3 m height.
- Height: Stem and total height must be measured with vertex, according to the user manual.
- Fire damage is scaled in 4 levels:
  - i) -F0: The tree does not show any fire damage.

ii) -F1: The tree is damaged, but alive and its survival is assured. In the case of doubts, trees are classified as F2. F1 trees with minor damage and good shape of the stem can be still considered as future trees.

iii) -F2: The tree is still alive, but damaged so severely as to leave some doubts about its survival. These trees cannot be considered as future trees.

iv) -F3: The tree is dead, apparently because of the fire.

- Health: Healthy or sick. When known cite the cause in observations: bacteria fungi, etc.
- Silvicultural category: classify the trees in: a) future crop tree, b) mature, c) competitor, d) indifferent. The future crop trees are carefully selected, since they assure the productivity of the forest long term.

  A mature tree must be in accordance with the minimum logging diameter. A tree with a diameter smaller than the value shown in Figure 55 be mature.

- Reference: at least 4 trees/plots should be used as reference to locate the central point, if necessary. Distance and angle must be measured with vertex and compass, respectively.
- Notes. Relevant information must be noted in this box.
- For regeneration a plot with a radius of 2.82 m, for trees with a DBH smaller than 10 cm and taller than 0.5 m, is set at 17.84 m to the East from the centre point of the plot.

  Tree name must be noted in all cases. When the DBH of the tree is lower than 5 cm, only height must be noted. When the DBH is between 5 and 10 cm, both height and DBH must be noted.

- Ending time: Set the starting time when the central point of the plot is reached.

Afata o Peteribí *(Cordia tricótoma)*	40 cm.
Arca, Visco o Viscote (*Acacia visco*)	30 cm.
Aliso del Cerro (*Alnus jorullensis var. Spachii*)	30 cm.
Algarrobo blanco (*Prosopis alba*)	40 cm.
Algarrobo negro (*Prosopis nigra*)	35 cm.
Azota caballo (*Luechea divaricata*)	30 cm.
Cebiles colorados o Curupay moro (*Piptadenia macrocarpa*)	30 cm.
Cedros salteño y coya (*Cederla balansae y C. lilloi*)	40 cm.
Espinillo, Palo cascarudo (*Pithecellobium scalare*)	30 cm.
Guyacán (*Caesalpinia paraguariensis*)	30 cm.
Horco cebil (*Piptadenia excelsa*)	30 cm.
Horco quebracho (*Schinopsis haenkeana*)	30 cm.
Lanza blanca (*Patagonula americana*)	25 cm.
Lapacho rosado y amarillo (*Tabebuia avellanedae, T. Lapacho*)	40 cm.
Laurel blanco, Peludo de la falda (*Ocotea puberula) (Phoebe porfiria)*	35 cm.
Mora amarilla (*Chlrophora tinctoria*)	40 cm.
Mistol (*Zizyphus mistol*)	25 cm.
Nogal criollo (*Juglans australis*)	40 cm.
Pacará (*Enterolobium contortisiliquum*)	40 cm.
Palma negra, Palmera de techo o Caranday (*Copernicia alba*)	7 cm.
Palo amarillo (*Phyllostylom rhamnoides*)	30 cm.
Palo blanco (*Calycophylom multiflorum*)	30 cm.
Palo barroso *(Blepharocaly gigantea*)	30 cm.
Palo santo (*Bulnesia sarmientoi*)	35 cm.
Pino del cerro (*Podocarpus parlatorei*)	30 cm.
Quebracho colorado santiagueño (*Schinopsis lorentzii*)	30 cm.
Quebracho blanco *(Aspidosperma quebracho blanco*)	30 cm.
Quina colorada (*Miroxylon peruiferum*)	40 cm.
Quina blanca *(Lanchocarpus lillloi*)	35 cm.
Roble (*Amburana caerensis*)	60 cm.
Sauce criollo o colorado (*Salix humboldtiana*)	30 cm.
Ceibo (*Erythrina falcata*)	30 cm.
Tarco o Jacarandá (*Jacaranda mimosifolia*)	30 cm.
Tipa amarilla (*Cascaronia astragalina*)	30 cm.
Tipa colorada (*Pterogyne nitens*)	40 cm.
Tipa blanca (*Tipuana tipu*)	35 cm.
Virarú (*Ruprechtia polystachya*)	30 cm.

Figure 55: minimum log diameter allowed in the province of Salta. Salta decree N° 15,142/60 (1960).

Inventory field sheet for Florestoona native forest				**Plot id:**	
Starting time:		**Ending time:**		**Date:**	/2016
Coordinates:	x:	y:		**Plot size**	Inner plot:
Forest type based on stratification:		**Based on observation:**			Outer plot:
Team:	Picture:	N	S	W	E
Slope:	**Weather conditions:**	Cloud coverage:		Temperature:	
Wind direction:	wind speed:	Others:			

	Species	DBH	Height		Fire damage (F0,F1, F2,F3)	Health	Silvicultural category	Reference		Notes
			Stem	Total				Distance	Angle	
	Local name	*cm*	*m*	*m*			*f,m,c,l*			
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
17										
18										
19										
20										
21										
22										
23										
24										
25										
	Regenration									
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

Observaciones:

Figure 56: Inventory field sheet used for the ground inventory of native forest in Florestoona.

8.3 Annex 3: EP inventory field sheet

Inventory field sheet for Florestoona enrichment planting				**Plot id:**
Starting time:	**Ending time:**	Plantation year		**Date:** /2016
Coordinates: x:		y:	**Plot size**	number of lines
Species of plantation		**Species for reposition**		number of plants
Team:	Picture:	N	S W	E
Slope:	**Weather conditions:**	Cloud coverage:		Temperature:
Wind direction: wind speed:		Others:		

	Species Local name or fail	DBH	Height		Fire damage (F0,F1, F2,F3)	Health	Stump (yes or not)	Regrowth (yes or not)	Notes
			Stem	Total					
		cm	m	m					
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									
17									
18									
19									
20									
21									
22									
23									
24									
25									
26									
27									
28									
29									
30									
31									
32									
33									
34									
35									
36									

Observaciones:

8.4 Annex 4: Outcome tables of clustering.

Table 35: Outcome table of clusters of hot and coldspots and random distribution of ACCI values at a threshold radius of 252 m. This table shows the area composition of forest (classified by fire severity strata) of every cluster given by Hot Spot Analysis (Getis-Ord Gi).*

Cluster type	Cluster ID	Fully stocked	Burned	Severely burned	Very severely burned	Bare land	Grand Total
Coldspot	17	37.6	56.8	97.2	194.5	17.9	404.0
	16	11.8	80.1	116.4	116.9	29.8	354.9
	27	0.1	4.9	9.0	7.4	0.6	22.1
	23	0.2	5.0	5.4	7.4	0.7	18.7
	20	0.0	2.2	7.8	4.3	0.0	14.2
	21	0.9	4.5	1.4	6.5	0.0	13.3
	22	0.7	3.5	3.0	2.8	0.1	10.1
	25	0.7	0.8	3.5	2.2	0.4	7.5
	24	0.0	1.4	2.7	2.2	0.1	6.4
	19	0.0	1.3	3.2	1.3	0.4	6.1
Subtotal		**51.9**	**160.4**	**249.4**	**345.5**	**50.0**	**857.3**
Random	18	174.2	676.4	431.5	321.5	9.0	1612.6
	32	23.3	107.2	75.6	34.3	0.7	241.1
	33	12.2	35.2	17.3	21.4	0.2	86.4
	30	5.6	12.5	11.6	6.6	0.9	37.2
	26	6.2	3.7	4.6	5.5	0.0	20.1
	35	3.8	3.3	4.8	3.8	0.3	16.0
	31	0.0	7.0	4.0	3.0	0.0	13.9
	28	1.4	5.4	2.0	4.0	0.0	12.9
	29	0.8	3.3	2.1	1.3	0.0	7.5
	34	0.4	0.8	2.3	3.7	0.2	7.4
Subtotal		**228.1**	**854.7**	**555.7**	**405.1**	**11.4**	**2054.9**
Hotspot	1	124.2	151.2	61.0	50.3	0.6	387.2
	3	50.5	105.4	50.1	21.1	0.7	227.9
	7	21.3	29.4	16.0	6.5	0.0	73.3
	2	15.8	28.7	14.8	10.7	0.0	70.0
	11	9.2	39.3	12.8	8.2	0.2	69.7
	10	5.9	10.0	3.5	3.0	0.0	22.3
	4	2.2	9.4	5.2	1.8	0.1	18.7
	8	3.8	6.8	3.0	0.0	0.0	13.6
	12	2.1	7.3	3.7	0.2	0.0	13.3
	6	0.9	7.2	2.2	2.2	0.0	12.5
	13	1.3	5.2	4.7	0.6	0.0	11.7
	9	2.3	5.2	2.4	0.4	0.1	10.5
	14	1.7	2.8	2.8	0.9	0.0	8.3
	15	1.3	3.6	2.2	0.3	0.0	7.4
	5	0.9	4.1	1.4	0.6	0.0	7.1
Subtotal		**243.2**	**415.7**	**186.0**	**106.9**	**1.7**	**953.4**
Total		523.2	1430.8	991.2	857.4	63.0	3865.6

Table 36: Outcome table of clusters of hot and coldspots and random distribution of ACCI values at a threshold radius of 252 m. This table shows the percentage composition of forest (classified by fire severity strata) of every cluster given by Hot Spot Analysis (Getis-Ord Gi).*

Cluster type	Cluster ID	Fully stocked	Burned	Severely burned	Very se-verely burned	Bare land	Weighte d ACCI
Coldspot	17	9.3	14.1	24.1	48.2	4.4	25.9
	16	3.3	22.6	32.8	32.9	8.4	25.9
	27	0.6	22.2	40.8	33.7	2.7	25.7
	23	0.8	27.0	28.7	39.9	3.6	25.6
	20	0.0	15.3	54.6	30.1	0.0	25.1
	21	7.1	33.7	10.3	48.9	0.0	30.2
	22	6.5	34.9	29.5	27.8	1.3	33.3
	25	8.7	10.0	46.9	28.8	5.6	27.5
	24	0.0	21.2	42.4	34.3	2.2	25.1
	19	0.0	20.8	51.8	20.7	6.6	26.1
Random	18	10.8	41.9	26.8	19.9	0.6	38.8
	32	9.7	44.5	31.4	14.2	0.3	39.8
	33	14.1	40.8	20.1	24.8	0.3	39.7
	30	15.2	33.5	31.1	17.7	2.5	39.2
	26	31.1	18.3	23.1	27.5	0.0	43.7
	35	23.9	20.5	29.8	23.8	2.0	40.3
	31	0.0	50.2	28.4	21.4	0.0	34.5
	28	11.1	41.7	15.9	31.3	0.0	37.2
	29	11.1	44.2	27.9	16.8	0.0	40.2
	34	5.8	10.3	31.5	49.8	2.6	23.2
Hotspot	1	32.1	39.1	15.8	13.0	0.1	51.4
	3	22.2	46.3	22.0	9.3	0.3	48.1
	7	29.1	40.1	21.9	8.9	0.0	50.7
	2	22.5	41.0	21.2	15.3	0.0	46.1
	11	13.3	56.4	18.3	11.8	0.2	45.0
	10	26.3	44.7	15.7	13.3	0.0	49.5
	4	11.8	50.3	27.9	9.5	0.5	43.0
	8	27.7	50.1	22.2	0.0	0.0	53.7
	12	15.4	54.6	28.1	1.8	0.0	47.5
	6	7.2	57.4	17.5	17.8	0.0	40.8
	13	11.0	44.2	39.9	5.0	0.0	42.1
	9	21.9	50.0	23.1	3.8	1.3	49.4
	14	20.5	34.1	34.1	11.3	0.0	44.1
	15	17.7	48.2	30.0	4.2	0.0	46.9
	5	12.1	58.7	20.3	8.9	0.0	45.4

Table 37: Outcome table of clusters of hot and coldspots and random distribution of ACCI values at a threshold radius of 309 m. This table shows the area composition of forest (classified by fire severity strata) of every cluster given by Hot Spot Analysis (Getis-Ord Gi).*

Cluster type	Cluster ID	Fully stocked	Burned	Severely burned	Very severely burned	Bare land	Grand Total
Coldspot	16	15.4	108.4	135.1	132.7	31.2	422.8
	15	45.1	66.9	111.0	211.7	19.9	154.8
	22	0.4	11.7	9.0	10.0	0.7	31.8
	27	0.1	4.5	8.5	8.3	0.6	22.0
	18	0.0	3.5	8.6	5.2	0.0	17.3
	21	0.7	5.4	4.4	4.9	0.1	15.5
	19	1.3	5.4	2.2	6.6	0.0	15.5
	20	0.3	1.7	1.9	2.0	0.0	5.9
Subtotal		**63.3**	**207.6**	**280.8**	**381.4**	**52.4**	**985.5**
Random	23	126.8	512.9	336.8	236.6	6.7	1219.8
	17	13.7	87.5	60.8	24.0	0.3	186.3
	28	11.2	27.7	14.9	19.9	0.2	73.9
	29	18.5	21.4	14.9	17.8	0.3	72.9
	25	2.5	14.4	15.7	6.8	0.0	39.4
	31	4.5	16.6	3.5	9.6	0.0	34.2
	24	4.6	10.7	9.9	5.4	0.1	30.8
	30	1.9	6.4	1.7	3.7	0.0	13.8
	33	3.4	3.3	3.9	2.6	0.0	13.1
	32	2.2	1.0	1.0	2.0	0.0	6.1
	26	0.0	2.5	1.9	1.5	0.0	5.8
Subtotal		**189.4**	**704.4**	**464.9**	**329.9**	**7.6**	**1696.2**
Hotspot	1	128.7	185.2	76.6	60.9	0.7	452.1
	7	45.9	78.7	39.5	26.7	0.1	190.9
	3	56.0	117.5	61.9	28.2	1.6	165.2
	10	11.4	52.0	19.6	13.0	0.5	96.4
	9	6.8	12.6	5.8	3.5	0.0	28.7
	4	2.8	13.0	5.7	1.8	0.1	23.5
	12	3.1	10.0	7.3	1.8	0.0	23.5
	8	5.1	8.9	7.1	0.4	0.0	21.5
	14	1.2	10.8	5.0	2.0	0.0	19.0
	6	2.4	9.3	4.1	3.1	0.0	18.8
	11	2.0	7.0	4.0	1.2	0.0	14.2
	2	2.5	5.9	3.7	1.7	0.1	13.9
	5	1.6	6.0	3.6	0.7	0.0	12.0
	13	0.8	1.9	1.7	0.9	0.0	5.4
Subtotal		**270.4**	**518.8**	**245.4**	**146.1**	**3.1**	**1183.8**
Total		523.2	1430.8	991.2	857.4	63.0	3865.6

Table 38: Outcome table of clusters of hot and coldspots and random distribution of ACCI values at a threshold radius of 309 m. This table shows the percentage composition of forest (classified by fire severity strata) of every cluster given by Hot Spot Analysis (Getis-Ord Gi).*

Cluster type	Cluster ID	Fully stocked	Burned	Severely burned	Very se-verely burned	Bare land	Weighte d ACCI
	16	3.6	25.6	31.9	31.4	7.4	27.3
	15	29.2	43.2	71.7	136.8	12.9	78.3
	22	1.2	36.8	28.4	31.6	2.1	29.9
Coldspot	27	0.6	20.5	38.5	37.8	2.7	24.6
	18	0.0	20.0	49.9	30.0	0.0	26.1
	21	4.2	35.1	28.6	31.4	0.4	31.6
	19	8.4	34.7	14.4	42.3	0.0	32.2
	20	5.3	28.9	32.7	33.8	0.0	30.8
	23	10.4	42.0	27.6	19.4	0.5	38.7
	17	7.4	46.9	32.6	12.9	0.2	39.3
	28	15.1	37.5	20.2	26.9	0.2	39.2
	29	25.4	29.4	20.4	24.5	0.4	43.5
	25	6.5	36.6	39.8	17.1	0.0	35.8
Random	31	13.3	48.4	10.2	28.1	0.0	40.5
	24	14.9	34.9	32.0	17.7	0.5	39.9
	30	14.0	46.1	12.6	27.0	0.0	40.5
	33	25.8	25.0	29.6	19.7	0.0	43.6
	32	35.3	16.8	15.6	32.5	0.0	45.0
	26	0.0	42.6	32.7	25.5	0.0	32.3
	1	28.5	41.0	16.9	13.5	0.2	49.7
	7	24.1	41.2	20.7	14.0	0.0	47.2
	3	33.9	71.2	37.5	17.0	1.0	75.0
	10	11.9	53.9	20.3	13.5	0.5	43.3
	9	23.9	44.0	20.1	12.2	0.0	48.1
	4	11.8	55.5	24.4	7.8	0.4	44.5
	12	13.1	42.6	31.1	7.7	0.0	41.0
Hotspot	8	23.9	41.6	32.9	1.6	0.0	49.3
	14	6.3	56.7	26.5	10.7	0.0	41.3
	6	12.6	49.2	21.6	16.5	0.0	42.2
	11	14.0	49.4	27.9	8.6	0.0	44.3
	2	18.1	42.1	26.3	12.5	1.0	44.1
	5	13.7	49.8	30.1	6.2	0.0	44.6
	13	15.4	35.5	30.9	17.4	0.0	40.2

Table 39: Outcome table of clusters of hot and coldspots and random distribution of ACCI values at a threshold radius of 357 m. This table shows the area composition of forest (classified by fire severity strata) of every cluster given by Hot Spot Analysis (Getis-Ord Gi).*

Cluster type	Cluster ID	Fully stocked	Burned	Severely burned	Very severely burned	Bare land	Grand Total
Coldspot	11	47.5	67.9	114.1	215.3	20.3	465.1
	12	18.5	123.5	146.2	138.4	31.1	457.8
	16	0.9	16.3	13.1	12.7	0.8	43.8
	27	0.1	3.6	7.2	8.6	0.3	19.9
	17	0.7	6.7	6.2	5.7	0.1	19.4
	14	0.0	3.5	8.6	4.0	0.2	16.3
	15	0.7	4.8	2.2	6.4	0.0	14.1
Subtotal		**68.4**	**226.3**	**297.6**	**391.2**	**52.9**	**1036.4**
Random	19	123.6	481.4	307.2	231.6	5.9	1149.5
	18	11.7	69.0	54.4	20.5	0.3	155.9
	23	14.1	18.0	13.6	16.5	0.3	62.5
	22	9.4	22.7	12.7	16.9	0.2	61.8
	21	2.1	15.2	13.5	6.7	0.0	37.5
	20	2.1	7.0	8.5	4.5	0.0	22.1
	25	2.6	3.3	4.0	1.6	0.0	11.4
	24	1.2	3.9	1.5	3.6	0.0	10.2
Subtotal		**166.7**	**620.4**	**415.3**	**302.0**	**6.6**	**1511.1**
Hotspot	2	137.2	200.8	82.9	66.2	0.6	487.7
	5	59.0	126.2	64.6	30.2	1.7	281.8
	1	48.7	90.8	43.1	32.0	0.1	214.6
	3	22.5	91.4	44.4	23.1	0.6	182.0
	9	6.9	18.2	9.8	4.2	0.0	39.2
	8	5.1	12.1	10.6	0.4	0.0	28.2
	10	1.7	15.6	6.6	1.9	0.0	25.8
	6	2.2	13.4	5.2	1.7	0.1	22.6
	4	4.5	8.8	4.8	3.6	0.0	21.6
	7	0.3	6.8	6.3	0.9	0.4	14.7
Subtotal		**288.1**	**584.1**	**278.3**	**164.2**	**3.5**	**1318.2**
Total		523.2	1430.8	991.2	857.4	63.0	3865.6

Table 40: Outcome table of clusters of hot and coldspots and random distribution of ACCI values at a threshold radius of 357 m. This table shows the percentage composition of forest (classified by fire severity strata) of every cluster given by Hot Spot Analysis (Getis-Ord Gi).*

Cluster type	Cluster ID	Fully stocked	Burned	Severely burned	Very severely burned	Bare land	Weighted ACCI
Coldspot	11	10.2	14.6	24.5	46.3	4.4	26.8
	12	4.0	27.0	31.9	30.2	6.8	28.2
	16	2.1	37.2	30.0	29.0	1.8	31.0
	27	0.7	18.1	36.3	43.2	1.6	23.5
	17	3.4	34.6	31.8	29.6	0.7	31.3
	14	0.0	21.5	52.6	24.4	1.5	27.0
	15	4.7	34.1	15.8	45.4	0.0	29.5
Random	19	10.8	41.9	26.7	20.1	0.5	38.7
	18	7.5	44.2	34.9	13.2	0.2	38.7
	23	22.6	28.7	21.8	26.5	0.4	41.4
	22	15.1	36.7	20.5	27.4	0.3	38.9
	21	5.6	40.5	36.0	17.8	0.0	36.0
	20	9.5	31.7	38.5	20.4	0.0	35.8
	25	22.3	28.6	34.8	14.3	0.0	43.3
	24	12.2	38.3	14.4	35.0	0.0	36.4
Hotspot	2	28.1	41.2	17.0	13.6	0.1	49.6
	5	20.9	44.8	22.9	10.7	0.6	46.7
	1	22.7	42.3	20.1	14.9	0.0	46.6
	3	12.3	50.2	24.4	12.7	0.3	42.8
	9	17.7	46.5	25.1	10.7	0.0	45.4
	8	18.2	43.0	37.5	1.2	0.0	46.5
	10	6.7	60.3	25.6	7.4	0.0	42.9
	6	9.8	59.3	22.8	7.6	0.4	44.3
	4	20.6	40.4	22.4	16.6	0.0	44.7
	7	1.9	46.6	42.6	6.4	2.4	36.6

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