Echeverría, C.M. et al., 2012. How landscapes change: Integration of spatial patterns and human processes in temperate landscapes of southern Chile. Applied Geography, 32(2), pp.822–831.

Available at https://doi.org/10.1016/j.apgeog.2011.08.014

How landscapes change: integration of spatial patterns and human processes in temperate landscapes of southern Chile

ABSTRACT

A comprehensive understanding of the patterns that occur as human processes transform landscapes is necessary for sustainable development. We provide new evidence on how landscapes change by analyzing the spatial patterns of human processes in three forest landscapes in southern Chile at different states of alteration (40% to 90% of old-growth forest loss). Three phases of landscape alteration are distinguished. In Phase I (40%-65% of old-growth forest loss), deforestation rates are < 1% yr^{-1}, forests are increasingly degraded, and clearance for pastureland is concentrated on deeper soils. In Phase II (65%-80%), deforestation reaches its maximum rate of 1 to 1.5% yr^{-1}, with clearance for pastureland being the main human process, creating a landscape dominated by disturbed forest and shrubland. In this phase, clearance for pastureland is the primary driver of change, with pastures expanding onto poorer soils in more spatially aggregated patterns. In Phase III (80%-90%), deforestation rates are again relatively low (< 1% yr^{-1}) and forest regrowth is observed on marginal lands. During this phase, clearance is the dominant process and pastureland is the main land cover. As a forest landscape is transformed, the extent and intensity of human processes vary according to the existing state of landscape alteration, resulting in distinctive landscape patterns in each phase. A relationship between spatial patterns of land cover and human-related processes has been identified along the gradient of landscape alteration. This integrative framework can potentially provide insights into the patterns and processes of dynamic landscapes in other areas subjected to intensifying human use.

Keywords: landscape classification, land cover change, fragmentation, deforestation, degradation

1. INTRODUCTION

The need for a comprehensive assessment of the relationships between landscape spatial patterns (spatial arrangement and composition of landscape elements) and human processes (forest fragmentation, forest degradation and deforestation by land use change) has been highlighted in recent decades in the context of global environmental change (Ferrier & Drielsma, 2010; Holmes et al., 2010; Liu & Taylor, 2002; Nagendra et al., 2004). Diverse studies on landscape fragmentation have demonstrated the close relationship between spatial patterns and human processes in many parts of the world (Cayuela et al., 2006; Echeverría et al., 2006; Fialkowski & Bitner, 2008; Gasparri & Grau, 2009). Some studies have shown that forest degradation by human activities such as livestock grazing and tree harvesting is related to changes in spatial patterns (Nandy et al., 2011). Similarly, other studies have revealed how deforestation associated with agricultural expansion and forest regrowth associated with land abandonment are closely linked to changes in landscape patterns (Abdullah & Nakagoshi, 2008; Zomeni et al., 2008). In addition to evaluating the spatial linkages between patterns and processes, there is a need to examine how human processes co-occur over time to change a landscape. Most research to date has focused on separately evaluating the impacts of forest loss, fragmentation, degradation and agricultural expansion on spatial patterns (An et al., 2008; Putz & Redford, 2010), whereas very few studies have analysed how human processes coexist over time and space in dynamic landscapes (Brandt & Townsend, 2006; Panta et al., 2008).

Different classifications of landscape change have been identified in terms of structural thresholds (Forman, 1995; McIntyre et al., 1996) or the prevalent land use (Hobbs & Hopkins, 1990). In addition to these classifications, a model that synthesizes four landscape states (intact, variegated, fragmented and relictual) was proposed by merging the previous classifications of landscape change (McIntyre & Hobbs, 1999). As in Forman's (1995) and McIntyre and Hobbs' (1999) models, the current classifications of landscape change are typically represented by a decrease in connectivity and remaining cover, and an increase in edge effects. However, these models do not provide specific responses of how spatial patterns and human processes interact at temporal and spatial scales. For instance, when, where and how do clearance, fragmentation and degradation of pristine forests occur as a forest landscape is transformed into an agricultural landscape? When and where can forest regrowth be observed in a changing landscape? There is a need to consider the landscape not only in structural terms, but also in relation to the complexity of human-environment interactions that occur and vary along a continuum of landscape alteration (Ferrier & Drielsma, 2010; Gutzwiller, 2002). It is necessary to refine current models of landscape change by integrating patterns of land cover change with processes relating to human activity.

Given the increasing emphasis on operationalizing the concept of landscape sustainability in the real world (Musacchio, 2011; Naveh, 2007), there is a need to further develop an understanding of how real landscapes change. While some studies have shown evidence of thresholds in simulated landscapes (Gustafson et al., 2006; Trani & Giles, 1999), very few studies have focused on detecting thresholds in real landscapes during the process of land cover change (Oliveira-Filho & Metzger, 2006). Analysis of such thresholds will inform the development of management and conservation strategies, which will differ according to the state of alteration of the landscape (Liu & Taylor, 2002; McIntyre & Hobbs, 1999).

The main goal of the present research is to refine the current models of landscape change using an integrative approach for analysing spatial patterns and human processes. In particular, we document changes in spatial patterns and human processes along a gradient of real forest landscape alteration in southern Chile. Then, we examine whether similar trends have been observed in other regions, with the aim of identifying generalizations.

2. MATERIAL AND METHODS

2.1 Study areas

Our research was conducted in three related landscapes located in the Los Lagos Region of southern Chile (40° 15’ S, 72° 41’ W and 44° 01’ S, 71° 43’W), which were all covered by near-continuous temperate forests until the early 1800s (Fig. 1). This zone is characterised by a rainy temperate climate with an oceanic influence and without dry periods (Di Castri & Hajek, 1976), with a mean annual precipitation of 2090 mm. The landscapes are located on an acidic, shallow, poorly-drained soil referred to as *ñadi* soil, which is classified as Gleysol (FAO-UNESCO, 1971). Most *ñadi* soil occupies the flatter parts of the landscapes, and occurs in association with better-drained soils also derived from volcanic ash that occupy the hilly parts of the landscapes (IRRI, 1984). Owing to drainage restriction, *ñadi* soil is not commonly used for crop cultivation after forest clearance (Carmona, 1981), but for livestock grazing (Torres, 1992). The landscapes are primarily dominated by Valdivian temperate rain forests, surrounded by a matrix of crops and pasturelands. These forests are recognised in two international initiatives for their conservation value: WWF Global 200 Ecoregions (Olson et al., 2001) and the Global Biodiversity Hotspots (Myers et al., 2000). Today, a gradient of landscape alteration can be observed, ranging from extensive areas covered by pristine forests to areas almost completely cleared for agricultural production:

Landscape 1 (L1) corresponds to an initial stage of landscape transformation located on Chiloé Island (Fig. 1). Approximately, 51% of the total land (1,681 km^2) is currently covered by relatively intact old-growth forest. Deforestation through logging and cultivation principally commenced in recent decades, owing to its isolation from the continent. L1 is considerably less populated than nearby continental areas. Over the last four decades, land clearance for agricultural expansion and logging for fuelwood have been the most important causes of forest destruction in L1 (Echeverría et al., 2008; Lara et al., 2002; Reyes, 2000).

Landscape 2 (L2) corresponds to an intermediate stage of landscape transformation in which 34% of the total land area (1,281 km^2) is currently covered by relatively intact old-growth forest. Clearance of forest habitats for agricultural land occurred mainly at the beginning of the 20th century. Large tracts of native forest disappeared during the 1980s and 1990s owing to an increase of woodchip export from native species and a rapid expansion of urban grounds.

Landscape 3 (L3) corresponds to an advanced stage of landscape transformation in which 26% of the total landscape (1,254 km^2) is currently covered by relatively intact old-growth forest. The area is characterised by an undulating hilly terrain in the foothills of the western part of the Andes Mountains (Fig. 1). As a result of European settlements in the area since the 1850s, intensive timber exploitation began in the area, allowing the establishment of grazing areas and crop cultivation (Donoso & Lara, 1995). Commercial plantations of *Eucalyptus* spp. have been established in the landscape.

2.2 Satellite data

To analyse the spatial and temporal changes of land cover types, a set of six Landsat satellite scenes taken in the summer were acquired at different points in time: 1985 (Thematic Mapper, TM), 1999 (Enhanced Thematic Mapper, ETM+) and 2007 (TM) for L1 and L2, and 1986 (TM), 1998 (ETM+) and 2006 (TM) for L3.

2.3 Pre-processing, classification and accuracy of the satellite data

Each image was geometrically, atmospherically and topographically corrected. Geometric correction was performed using "full processing" module in PCI Geomatics and ENVI. This consisted in the transformation of each image using GCPs (ground control points) and a 2nd order polynomial mathematical model. The satellite images were georeferenced separately by locating approximately 70 GCPs in each image and producing corresponding reference maps. The geometric accuracy ranged from 0.11 to 0.29 pixels, corresponding to 3.3 to 8.7 m. Atmospheric correction was applied to all of the scenes, transforming the original radiance image to a reflectance image (Chávez, 1996). The topographic correction was conducted for each scene using the method proposed by Teillet et al. (1982) in order to remove shadows in hilly areas. Supervised, maximum likelihood classifications were performed on each of the three images to classify the land cover types using training locations, obtained from field surveys (Chuvieco, 1996). Two types of data were used in the image interpretation. "Catastro" is a GIS- based data set of thematic maps derived at 1:50,000 scale from aerial photographs and satellite imagery between 1994 and 1997 (CONAF et al., 1999). The Catastro data was also used to develop a set of categories of land cover type for the present work. A second reference group was comprised of 70 control points of field visits made in July 2007. Land cover types that did not show changes in the last 20 years were recorded in the field by consulting local farmers. Patches of old-growth forests were also recorded in the field to assist the interpretation of earlier images.

The overall accuracy of the classification of each image was estimated by constructing confusion matrices between reference data and classified data (Chuvieco, 1996). The accuracy was assessed by ground validation of 260 points visited between 1998 and 2008. For the TM images of 2006 and 2007, reference data (250 points for each image) was obtained in 2007 from additional field observations of land cover types that did not exhibit changes between images over time. The overall accuracy values corresponded to 89.6% for 1985 image, 91.9% for the 1999 image, and 93.2% for 2007 image in L1 and L2. These percentages were 90.1% for 1986 image, 93.6% for 1998 image and 91.3% for 2006 image in L3. The accuracy of old-growth forest reached 95.9% in 1985, 96.1% in 1999, and 93.4% in 2007; and 91.1% in 1986, 90.1% in 1998 and 92% in 2006. The high percentages of overall accuracy of the images revealed that the supervised classification, which was strongly supported by ground-based information, provided a suitable identification of land cover types in each of the satellite scenes processed.

2.4 Land cover types

The following categories of land cover were identified from each image: 1) pasture land (for livestock grazing); 2) shrubland (land dominated by shrub species with < 10% tree cover and originating from the logging of tree species in disturbed forests or old-growth forest or from natural succession due to land abandonment); 3) arboreus shrubland (similar origin to shrubland but with 10-25% tree cover); 4) disturbed forests (originated from logging of tree species in old-growth forest or from natural succession); 5) old-growth forest (pristine forest or almost intact mature forest of broad-leaved evergreen tree species); 6) commercial plantation (mainly *Eucalyptus* species for pulp industry); 7) bare ground; and 8) urban areas.

2.5 Temporal and spatial patterns of land cover change

For each study landscape we analyzed the classified maps using ArcGIS 9.3.1 (ESRI, 2009) and its extension Spatial Analyst to estimate the area of the landscape occupied by each land cover type. A cross-tabulation procedure between land cover maps was undertaken with IDRISI Andes (Clark-Labs, 2007) to determine land cover transitions for each time interval. The smallest patches (< 5 pixels) were removed from all of the images to reduce errors during image comparison.

Relationships between forest cover and soil depth were examined to assess the spatial pattern of agricultural expansion in flat areas susceptible to livestock grazing (<5% slope). Soil depths were obtained for each soil series (CIREN, 2003) and were overlaid on forest cover maps of the earliest study year (1985 and 1986).

2.6 Loss, degradation and fragmentation of old-growth forest

Land cover was grouped into forest or non-forest categories using ARC GIS 9.3.1 (ESRI, 2009) to estimate and map the spatial pattern of forest loss. A compound-interest formula was used to determine the annual rate of deforestation in each study landscape (Echeverría et al., 2007a). The spatial pattern of forest degradation was analysed examining the conversion of i) old-growth forest to disturbed forest, arboreus shrubland or shrubland; and ii) from disturbed forest to arboreus shrubland or shrubland. The spatial pattern of forest fragmentation was assessed using the following indices of FRAGSTATS (Mcgarigal et al., 2002): a) patch density (number of patches per 100 hectares), b) proximity index (ratio between the size and distance of all patches whose edges are within a specified search radius of the local patch (1 km) and c) largest patch index (percentage of area accounted for by the largest forest patch). These indices provide information about the patterns of subdivision of forest patches, in which forest cover becomes disaggregated and isolated across the landscape (Forman & Godron, 1986).

3. RESULTS

3.1 Changes in landscape composition

In L1 (initial stage of landscape transformation), old-growth forest was the predominant land cover type with 52% of the landscape in 1985 (Fig. 2). All of the human-related land cover types such as disturbed forest, arboreus shrubland, shrubland and pastureland exhibited the highest increase in area over time. In contrast old-growth forest, the only non-human related land cover type, showed a decline in the area occupied in the landscape. By 2007, commercial plantations represented 1% of the landscape (Fig. 2).

In L2 (intermediate stage of landscape transformation), old-growth forest was the predominant land cover type with 34% in 1985, whereas in 2007 arboreus shrubland and pastureland were the major land cover types, each representing 27% of the landscape (Fig. 2). Similarly to L1, all human-related land cover types exhibited an increase in area over time, while old-growth forest decreased dramatically from 34% in 1985 to 7% in 2007. Disturbed forest and arboreus shrubland were the land cover types that showed the highest increase in area across the landscape. Commercial plantations of exotic species occupied 1% of the landscape.

In L3 (advance stage of landscape transformation), pastureland was the predominant land cover type across the study period (Fig. 2). Over the whole study period, disturbed forest and arboreus shrubland increased in area, but at a lower increment compared to L1 and L2. In contrast to L1 and L2, a reduction of shrubland from 20% to 13% was observed in L3. In 2006, forest plantation of exotic species occupied a greater proportion than in L1 and L2; equivalent to 2% of the landscape.

3.2 Trajectories of land cover change

In L1, the major contributions to the net change were the conversion of old-growth forest to arboreus shrubland during the first time interval and to disturbed forest in the second one (Fig. 3). Another important trajectory of change corresponded to the conversion of 19% of arboreus shrubland to pastureland (Fig. 3). Similar to L1, the major trajectory of change in L2 was the formation of disturbed forest through degradation of old-growth forests (Fig. 3). Similar but less pronounced trajectories of forest degradation were identified in L3. Contrary to the trends observed in L1 and L2, 12% of the shrubland exhibited forest re-growth to secondary forest (disturbed forest) during the first time interval. Similarly, 7% of the pastureland regenerated to arboreus shrubland (Fig. 3).

3.3 Changes in forest cover

In L1, forest loss (old-growth forest plus disturbed forest) occurred at a rate of 1%yr^{-1}, with the highest loss during the last time interval at a rate of 1.4% yr^{-1}. In L2, forest loss also occurred at a rate of 1% yr^{-1}, but the highest loss was observed in the first time interval at a rate of 1.1% yr^{-1}. In L3, forest loss was at a lower rate (0.8 % yr^{-1}) than in L1 and L2. During the first time interval, deforestation occurred at a rate of 1.1 yr^{-1}, while in the second interval this rate decreased to 0.4% yr^{-1}.

Largest patch index and proximity index declined consistently over time in the three study areas (Fig 4a,c). The greatest absolute decline in these two indices was observed in L1, followed by L2 and then L3. In particular, the faster decline was observed in L1 where the proportion of the landscape occupied by the largest patch decreased from 18% to 6.5% and when the old-growth forest loss increased from 49% to 79% (Fig. 4a). Moreover, isolation of old-growth forest patches was more rapid in L1 than in the other landscapes (Fig. 4c).

This change in the spatial pattern of old-growth forest in L1 was associated with a consistent increase in patch density (Fig. 4b). In L2 this index remained constant (0.42) when the loss of old-growth forest accounted for 71% of the landscape. However, patch density declined to 0.35 when old-growth forest loss reached 90%, which denotes the elimination of forest fragments and not the division of forest patches as observed in L1. In L3, the index was also constant at 0.35 when the old-growth forest loss reached up to 83% of the landscape. Nevertheless, patch density showed an increase to 0.43, despite the progressive reduction of old-growth forest. This increase in patch density was observed only in L3 and is the result of the creation of new forest patches (Fig. 4b).

3.4 Phases of forest landscape alteration

We identified the following three phases of forest landscape alteration (Fig. 5):

Phase I: Old growth forests lost from 40% to 65% of their original extent. Forest degradation was the major human-related process while forest clearance tended to decline. Maximum degradation was observed when the old-growth forest cover was between 30% and 40% and the deforestation rate was less than 1% yr^{-1}. Large fragments of old-growth forest were rapidly divided and isolated. Pastureland expansion occurred primarily in forest areas located in deep soils.

Phase II: Old growth forests lost from 65% to 80% of their original extent (Fig. 5). Landscape was increasingly affected by forest clearance while forest degradation tended to decline. The landscape became more dominated by disturbed forest and shrubland. The deforestation rate was higher than in Phase I (up to 1.5% yr^{-1}). Old-growth forest was characterised by a loss of fragments rather than a division of them as recorded in Phase I. A change in direction in patch density was observed when old-growth forests dropped to 30% of the landscape. Deeper soils (>1 m depth) presented a lower amount of old-growth forest cover than in Phase I. The highest rates of forest plantations of exotic species are observed in this phase.

Phase III: Old growth forests lost from 80% to 90% of their original extent (Fig. 5). This landscape was more affected by forest clearance than by degradation. The landscape became dominated by pastureland. The deforestation rate was lower (0.4 to 1.0%yr^{-1}) than in Phase II and relatively similar to Phase I. A slight increase in the number of forest patches was associated with changes from shrubland to secondary forest in some specific sites. Commercial forest plantations of exotic species continued to be established across the landscapes but at a lower rate than in Phase II.

4. DISCUSSION

Previous attempts to classify landscape alteration have distinguished four states of habitat destruction based on structural attributes of the landscape (Hobbs & Hopkins, 1990; McIntyre & Hobbs, 1999): intact (>90% of habitat remaining), variegated (60-90%), fragmented (10-60%) and relictual (<10%). On the other hand, Forman (1995) identifies five main ways in which humans can alter a landscape spatially: perforation, dissection, fragmentation, shrinkage, and attrition. Although all of these models of landscape change recognise a continuum of habitat modification and destruction, they do not illustrate how such processes gradually alter landscape composition and configuration (spatial patterns). Also, these previous models fail to consider explicitly the complex linkages between spatial patterns and human processes that occur as a forest landscape is transformed by anthropogenic activities.

In the present work, we documented the interaction between spatial patterns and human processes of land cover change to examine how real landscapes change. In particular, we observed distinctive spatial patterns and human processes as the loss of old-growth forests increased from 40% to 90% of its original extent (Fig. 5). For values of forest loss lower than 40%, it is highly probable that forest loss and fragmentation are the major processes of landscape transformation (Echeverría et al., 2008).

In Phase I, forest degradation and fragmentation increase to its maximum when old-growth forest loss is between 60% and 70%. Forest logging for firewood and timber, livestock grazing and fire are more intense and are the main driving factors that lead to a forest degradation in this phase (Echeverría et al., 2007b). In the study areas, forest degradation and clearance for agriculture are highly related to subsistence farms, which use the forest in an unsustainable way and are affected by the lack of productive alternatives (Carmona et al., 2010; Elmúdesi & Cox, 2006). Increasing trends in forest degradation have also been reported for accessible rain forests in primary forest-dominated landscapes in Papua New Guinea (Shearman et al., 2009), where the primary forest is degraded owing to forest logging. Diverse forest landscapes around the world have exhibited a consistent fragmentation of forest habitat at initial stages of landscape alteration (Echeverría et al., 2006; Ranta et al., 1998; Zipperer et al., 1990). Forest fragmentation is not a random process, but it follows a specific pattern across the landscape (Lindenmayer and Fischer 2006). In the present study, fragmentation occurred preferably in forests located in deeper soils. Evidence from other studies shows that changes in spatial pattern are driven by various landscape attributes (Iverson, 1988) such as soil fertility (Alig et al., 2005). These changes can be easily observed at this state of landscape alteration, where areas more profitable for agriculture are associated with forest fragmentation, while in areas with poorly drained soils agricultural production is almost unfeasible and fragmentation does not occur (Baldi et al., 2006).

In Phase II there are substantial areas of degraded forests that are susceptible to clearing for pastureland. A similar trend was observed in Belize, where the major human process is the clearance of forests for cattle when 67% of the forest cover has been eliminated (Wyman & Stein, 2010). The highest rate of deforestation was observed in Phase II of the gradient of landscape alteration. Similarly, high rates of deforestation have been reported in other study areas when between 60% and 80% of forest cover has been lost (Cayuela et al., 2006; Ite & Adams, 1998; Schulz et al., 2010).

In Phase II, the loss of old-growth forest brings substantial changes in landscape connectivity, with changes in metric directions and landscape composition. A steady increase of patch density until

50% of forest cover has been lost, followed by a decline in the patch density is also observed in studies conducted using modelled deforestation maps (Trani & Giles, 1999) and satellite imagery-based maps (Zipperer et al., 1990). These studies also conclude that forest contiguity declines with each stage of deforestation, dropping rapidly after aggregate forest loss surpassed 75%.

In Phase II, forest cover tended to decline in deeper soils in the study landscapes. Consistent with previous studies (Fu et al., 2006; Sklenicka & Salek, 2008), forests on high quality, deeper soils, are progressively cleared for pastureland. At this stage of landscape alteration, most of the remaining old-growth forest has progressively been converted into shrubland or pastureland as a consequence of a greater need for forage. Diverse landscapes with conversion of forest into cropland and pastureland exhibit an extensification of agricultural land (Mottet et al., 2006), as producers respond to changes in food consumption habits and market requirements (Matson et al., 1997). However, this general trend to homogenisation of the landscape can also be altered as a consequence of enforced reforestation laws (Zeledon & Kelly, 2009). This was observed in the study area, where the highest rate of subsidised plantations of exotic species such as *E. globulus* and *E. nites* were concentrated in this phase of landscape alteration.

In Phase III landscapes become more dominated by pastureland and clearance is the major human process. Landscapes with no limits to agricultural expansion can reach the spatial pattern observed in Phase III that describes a largely deforested landscape with few small and poorly connected forest patches, surrounded by degraded forest or pasture land (Gasparri & Grau, 2009). At this stage, accessibility becomes a key variable in determining when forest patches would be cleared as the landscape is transformed to agricultural land (Nagendra et al., 2003). If the current rates of afforestation with exotic species remain constant, it is possible to expect a further homogenisation of the landscape by one or two dominant tree species (Echeverría et al., 2006; Padilla et al., 2010).

Similar to other landscapes (Evans & Kelley, 2008), the slight increase in the number of forest patches and the changes in trajectories indicate the existence of some forest regrowth in deforested areas. This can be related to land abandonment where forest returns as a result of unregulated productive cycle (Carmona et al., 2010; Geri et al., 2010). Recent research conducted in the study landscapes also confirm land abandonment in remote areas located far from production centres, which produce low yields at high cost (marginal land) (Carmona et al., 2010; Díaz et al., 2011). Forest regrowth in accessible areas, resulting from the abandonment of marginally productive agricultural farms owing to agricultural intensification (Nagendra et al., 2003), has been observed after a period of forest loss and fragmentation (Evans & Kelley, 2008). Forest regrowth can lead to a defragmentation (Hale et al., 2001) of forest patches in marginal lands while in other places old-growth forest is progressively cleared (Fig. 7).

CONCLUSION

The processes of clearance, fragmentation and degradation of forest cover as well as forest regrowth operate in spatially differentiated patterns and their occurrences vary over time according to the phase of landscape alteration. Forest clearance for pastureland can be expected along the entire gradient of landscape alteration, while forest fragmentation and degradation are only dominant until certain thresholds of forest loss. In advanced states of landscape alteration, forest regrowth appears as a process modifying the spatial pattern of the landscape.

The three phases of landscape alteration offer a framework that could potentially be applied and further tested in other regions, leading towards a generalised understanding of how landscapes change in the real world.

ACKNOWLEDGEMENTS

This research was made possible by funding from FONDECYT Chile projects Nº1080408 and Nº 1085877, and the European funded project BIOCORES ICA-CT-2011-10095. The authors are grateful to Rodrigo Fuentes, Guillermo Machuca and Gustavo Bolados from LEP (Laboratory of Landscape Ecology, U. of Concepcion) for their assistance and to Juan Gamín and Fernando Moraga from Corporación Nacional Forestal (CONAF) for making their databases available to us.

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FIGURE CAPTIONS

Figure 1. Location of study areas in southern Chile representing a gradient of landscape alteration states: L1 (initial), L2 (intermediate), and L3 (advanced).

Figure 2. Temporal variation in the proportion of the major land cover types in L1 (initial stage of landscape alteration), L2 (intermediate), and L3 (advanced).

Figure 3. Major trajectories of land cover change and their contributions to net change in percentage of the total area of the respective land cover types in L1 (initial stage of landscape alteration), L2 (intermediate), and L3 (advanced). Lines represent net changes > 5%.

Figure 4. Temporal variations in landscape pattern indices for native forest cover in the three study areas.

Figure 5. Temporal variation of major landscape patterns and processes observed along a gradient of loss of old-growth forest in three study landscapes in southern Chile. Forest regrowth is the transition from pastureland to shrubland and arboreus shrubland; forest clearance is the transition from old-growth forest, disturbed forest, arboreus shrubland and shrubland to pastureland; forest degradation is the transition from old-growth forest to disturbed forest, arboreus shrubland and shrubland.

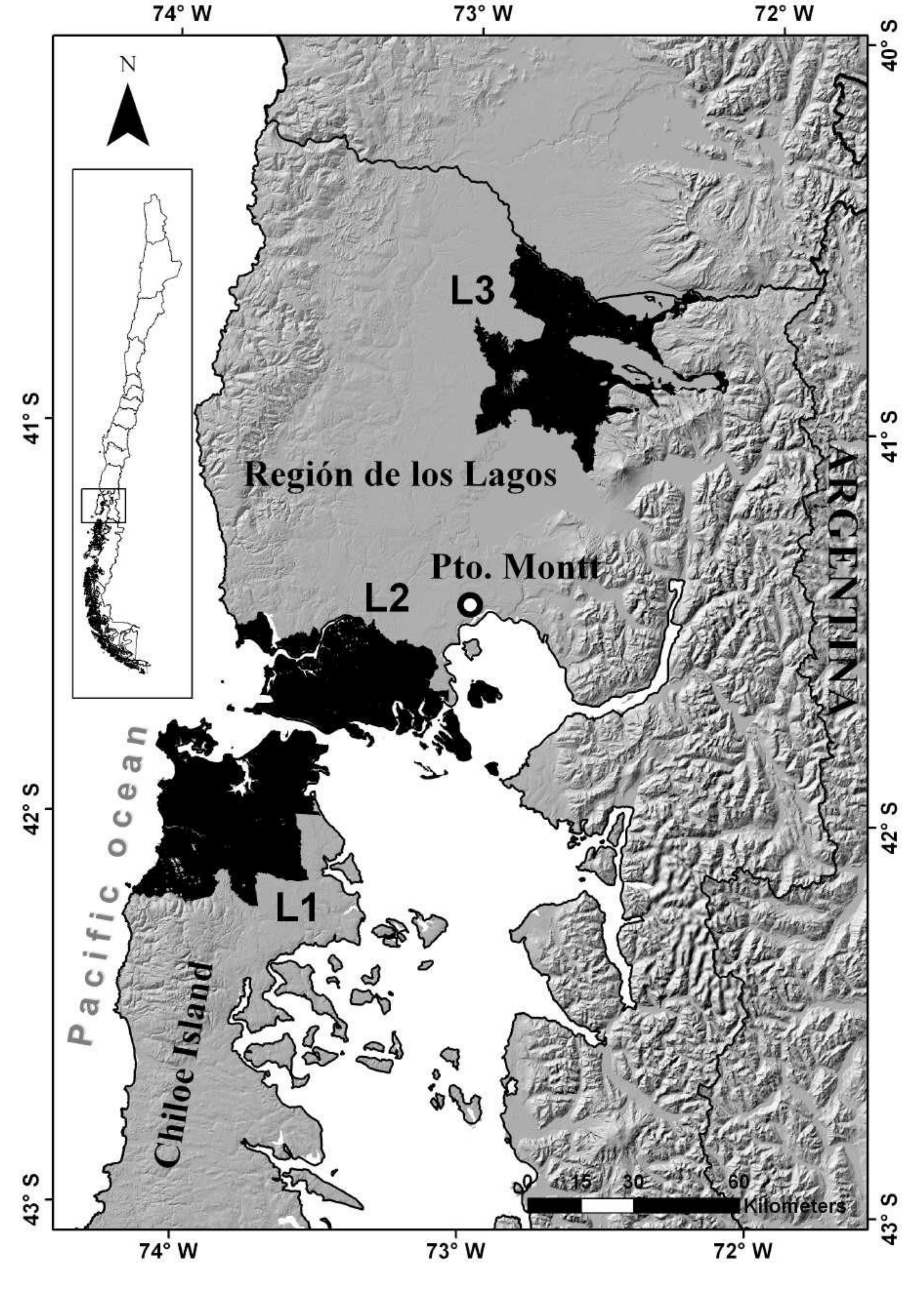

74° W
73° W
72° W
40° S
41° S
42° S
43° S
N
L3
L2
L1
Región de los Lagos
Pto. Montt
ARGENTINA
Pacific ocean
Chiloe Island
0
15
30
60
Kilometers

Figure 1.

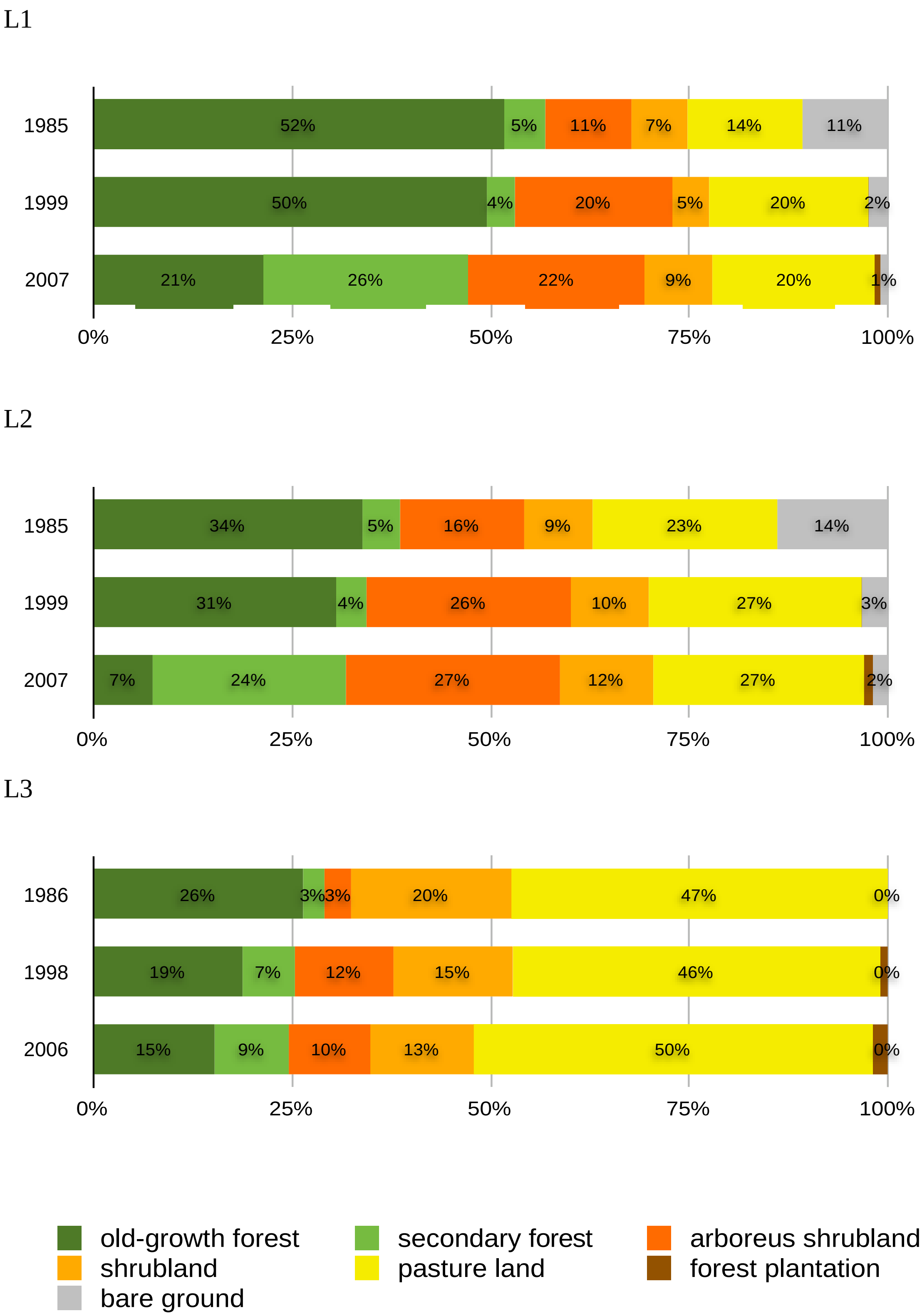

L1
1985
52%
5%
11%
7%
14%
11%
1999
50%
4%
20%
5%
20%
2%
2007
21%
26%
22%
9%
20%
1%
0%
25%
50%
75%
100%
L2
1985
34%
5%
16%
9%
23%
14%
1999
31%
4%
26%
10%
27%
3%
2007
7%
24%
27%
12%
27%
2%
0%
25%
50%
75%
100%
L3
1986
26%
3%
3%
20%
47%
0%
1998
19%
7%
12%
15%
46%
0%
2006
15%
9%
10%
13%
50%
0%
0%
25%
50%
75%
100%
old-growth forest
secondary forest
arboreus shrubland
shrubland
pasture land
forest plantation
bare ground

Figure 2.

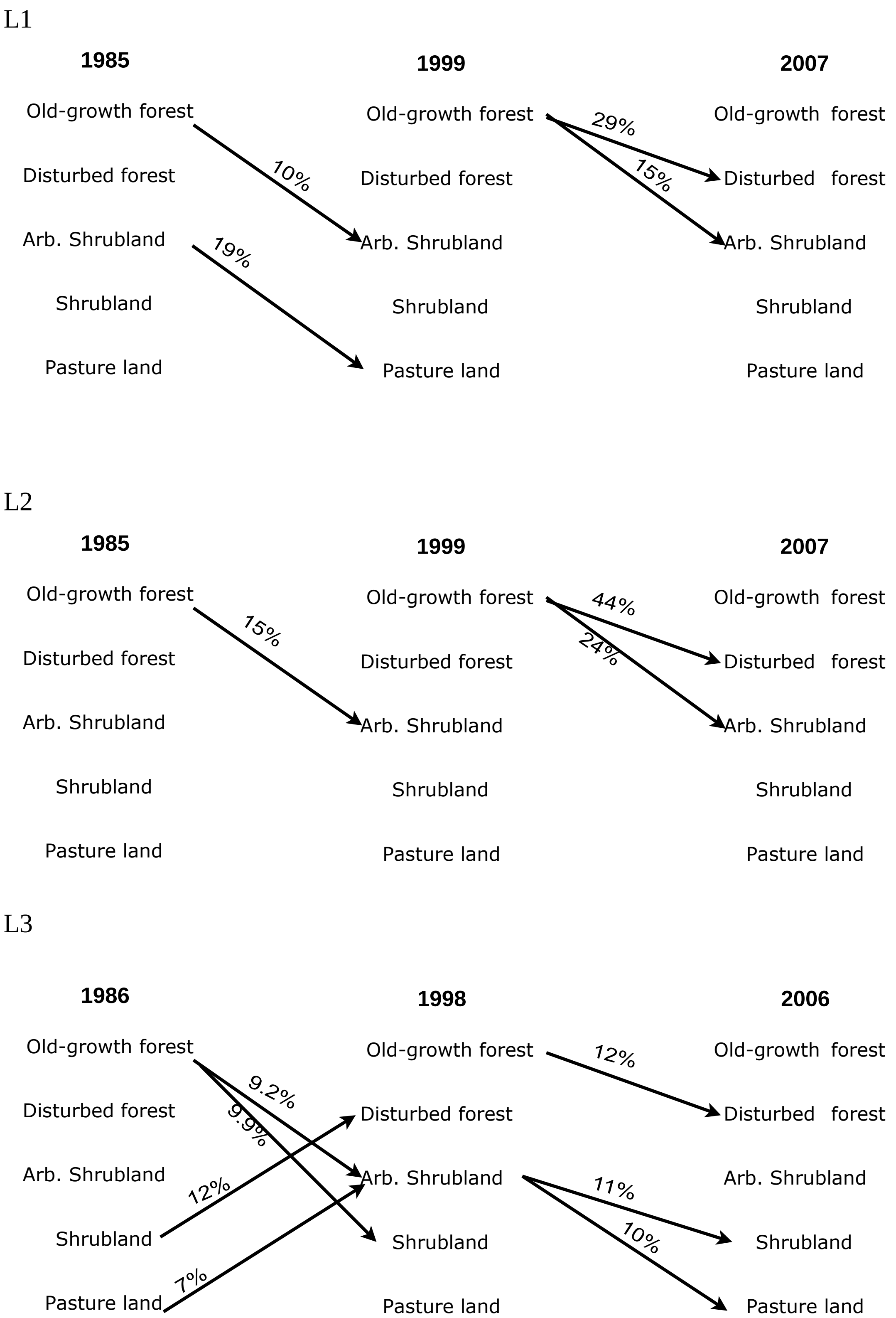
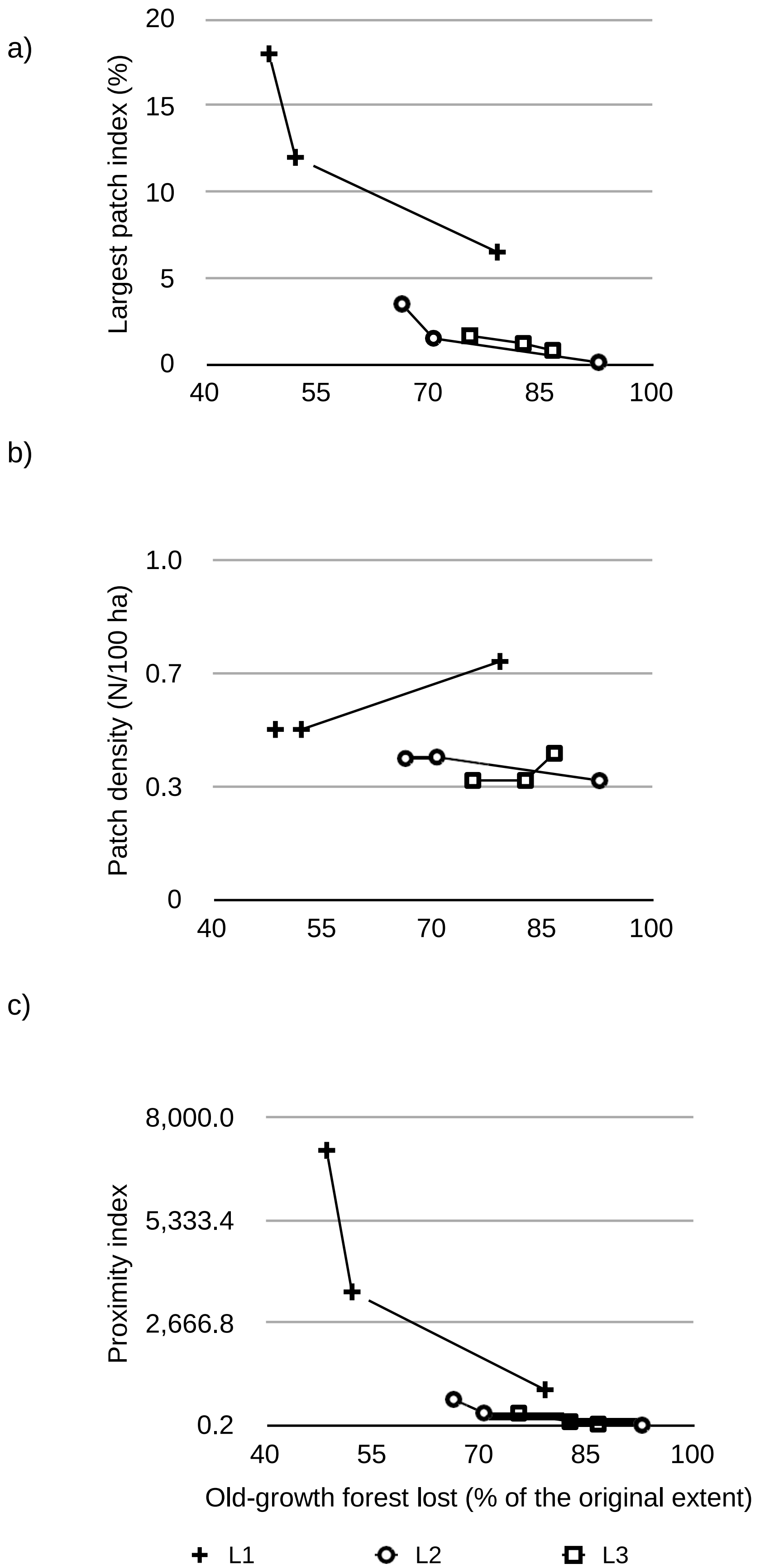

L1
1985
1999
2007
Old-growth forest
Disturbed forest
Arb. Shrubland
Shrubland
Pasture land
10%
19%
29%
15%
L2
1985
1999
2007
Old-growth forest
Disturbed forest
Arb. Shrubland
Shrubland
Pasture land
15%
44%
24%
L3
1986
1998
2006
Old-growth forest
Disturbed forest
Arb. Shrubland
Shrubland
Pasture land
9.2%
9.9%
12%
7%
12%
11%
10%

Figure 3.



a)
Largest patch index (%)
20
15
10
5
0
40
55
70
85
100
b)
Patch density (N/100 ha)
1.0
0.7
0.3
0
40
55
70
85
100
c)
Proximity index
8,000.0
5,333.4
2,666.8
0.2
40
55
70
85
100
Old-growth forest lost (% of the original extent)
L1
L2
L3

Figure 4.

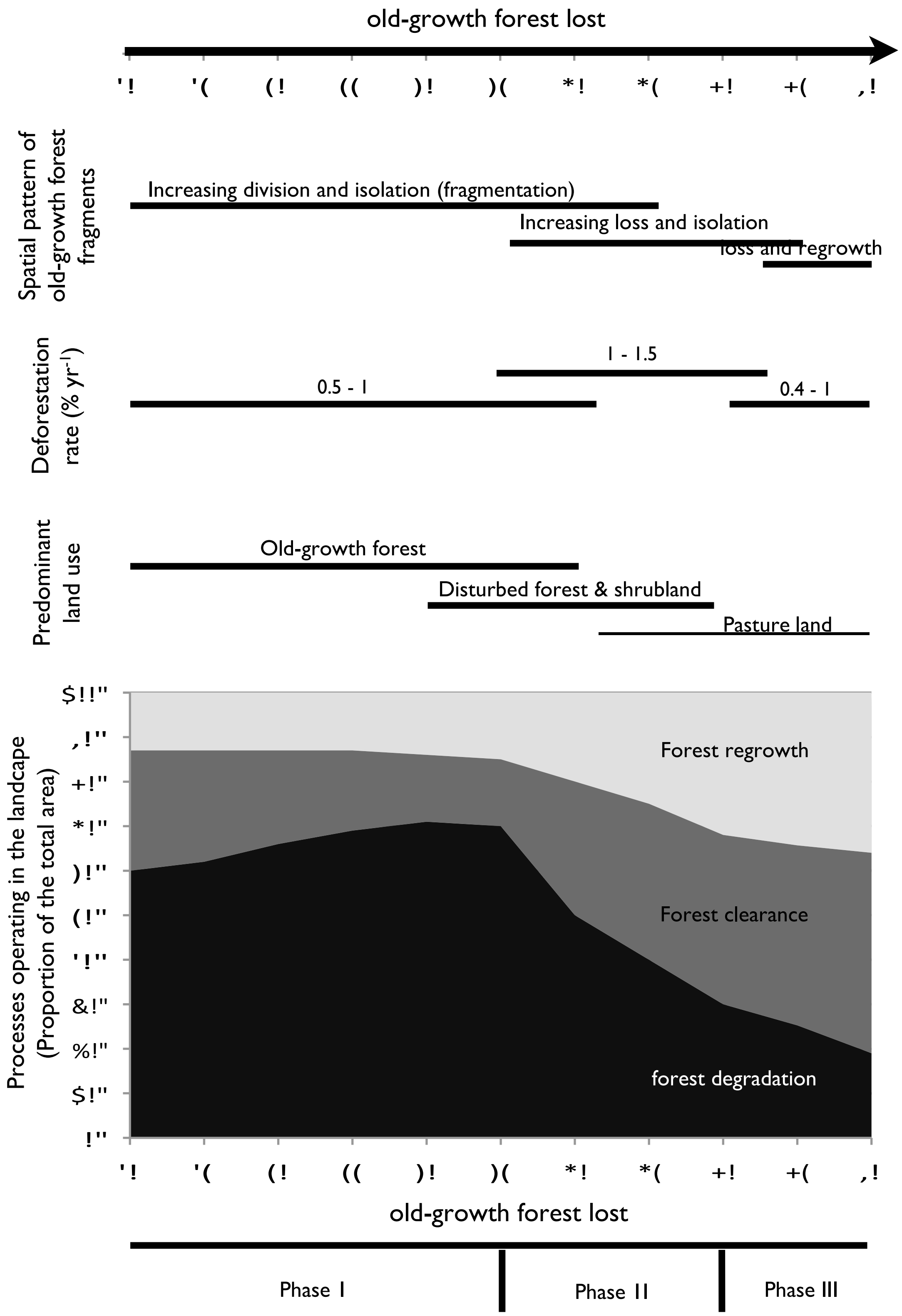

old-growth forest lost
Spatial pattern of old-growth forest fragments
Increasing division and isolation (fragmentation)
Increasing loss and isolation
loss and regrowth
Deforestation rate (% yr-1)
1 - 1.5
0.5 - 1
0.4 - 1
Predominant land use
Old-growth forest
Disturbed forest & shrubland
Pasture land
Processes operating in the landscape (Proportion of the total area)
Forest regrowth
Forest clearance
forest degradation
old-growth forest lost
Phase I
Phase II
Phase III

Figure 5.