Universitat de Lleida

A computacional model to predict land-use and cover changes in mountain landscapes

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University of Lleida
Department of Mathematics

A COMPUTATIONAL MODEL TO PREDICT LAND-USE AND COVER CHANGES IN MOUNTAIN LANDSCAPES

Ph.D. Dissertation

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School of Agrifood and Forestry Science and Engineering (ETSEA)

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Ph.D. Dissertation

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to my family

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"And are there countries with no mountains, father?"

"Pare, hi ha països sense muntanyes?"

„Giebt's Länder, Vater, wo nicht Berge sind?"

"Padre, ¿hay países sin montañas?"

Friederich Schiller (1804). *Wilhelm Tell.* Act 3, Scene 3, line 1786.

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Abstract

Since the second half of the 20th century, an expansion of the forest in European mountain areas has been observed. This transformation of the Alpine landscape is caused by changes in the land uses. An intensification process occurs to the surfaces most suitable for agriculture and livestock farming, while the grasslands farthest from villages and less accessible, face a reduction of the intensity of land use, so that these surfaces are progressively encroached by scrub and forest. Large parts of these agricultural surfaces are semi-natural meadows and pastures of great ecological and aesthetic value, receiving, therefore, a certain degree of protection.

P systems are bioinspired computational models that allow the modelling of complex ecosystems, in which a large number of actors evolve and interact with each other and with the environment. The evolution of the traditional agricultural landscape has been modelled in two Alpine regions: the high Catalan Pyrenees and the Stubai Valley, in the Central Alps. In these regions, three simulated scenarios have been established according to the intensity of the agricultural land use: (1) a continuation of the observed farming trends, or maintenance of the *status quo*, (2) significant and (3) strong stocking rate reductions.

The results show how the traditional agricultural surfaces decrease in all simulated scenarios in both study areas. In the Pyrenees, the surfaces located between 1700 and 2600 m are those that lose the greatest proportion of agricultural surface. The largest reforestation occurs between 2200 and 2600 m, being especially pronounced on gentle and moderate slopes (≤30°). In the Alps, the most important loss of agricultural surface, subsequently reforested, is expected to occur in the altitudinal ranges between 1500 and 2150 m. The traditional cultural mountain landscape evolves as the livestock stocking rate reduces. Annual variations in the censuses of goats, sheep, cows and mares have a significant effect on landscape changes. However, the effect of cattle has a greater importance, both for its nutritional requirements and its number in the study areas.

On the one hand, the reforestation of abandoned pastures and meadows regulates the ecosystem services, such as the hydrology, the carbon storage and the increase in soil stability. On the other hand, the growth of the forest reduces, for instance, the biodiversity, the quality and quantity of pastures and the scenic beauty of landscapes, transforming the heterogeneous agricultural mountain landscape into a homogeneous landscape dominated by forest. These effects of reforestation should be borne in mind when planning the land management policies.

As a general conclusion, new really efficient policies on the promotion and support of traditional agricultural and livestock farming land uses should be applied, including the participation of all involved actors in the decision making, in order to preserve the high mountain landscape. In this sense, the model aims to become a tool that helps to preserve the cultural and ecological heritage for future generations, before it disappears definitively.

Resum

D'ençà de la segona meitat del segle XX s'ha observat una expansió del bosc a les zones de muntanya europees. Aquesta transformació del paisatge alpí està originada per canvis en els usos del sòl. Les superfícies més aptes per a l'agricultura i la ramaderia pateixen un procés de intensificació, mentre que en aquelles superfícies més allunyades dels nuclis habitats i amb una accessibilitat menor es redueix la intensitat de l'ús del sòl que s'hi practica i són recolonitzades progressivament per matolls i pel bosc. Una gran part d'aquestes superfícies agrícoles són prats i pastures semi-naturals de gran valor ecològic i estètic, per la qual cosa disposen d'un determinat grau de protecció.

Els P systemes són models computacionals bioinspirats que permeten la modelització d'ecosistemes complexos en què un gran nombre d'actors evolucionen i interactuen entre ells i amb el medi. L'evolució del paisatge agrícola tradicional s'ha modelitzat en dues regions alpines: els alts Pirineus catalans i la Vall de Stubai, als Alps centrals. En aquestes s'han establert tres escenaris a simular d'acord a la intensitat de l'activitat agrícola: (1) continuació de la tendència ramadera observada, o manteniment del *status quo*, (2) reducció significativa i (3) molt forta de la càrrega ramadera.

Els resultats obtinguts mostren com la superfície agrícola tradicional es redueix en tots els escenaris futurs simulats en ambdues àrees d'estudi. Als Pirineus, les superfícies situades entre 1700 i 2600 m d'altitud són les que perden una major proporció de superfície agrícola. La major reforestació es produeix entre 2200 i 2600 m, essent superior sobre pendents moderades (≤30°). Als Alps, la pèrdua més important de superfície agrícola, posteriorment reforestada, es preveu que es produeixi al rang comprès entre 1500 i 2150 m d'altitud. El paisatge cultural tradicional de muntanya evoluciona a mesura que es redueixen els animals domèstics. Les variacions anuals en els censos de cabres, d'ovelles, de vaques, i d'egües tenen un efecte significant en el canvis en el paisatge. Tot i això, les vaques són l'animal, l'efecte del qual té un pes major, tant per les seves necessitats alimentàries com pel seu nombre en totes dues àrees d'estudi.

D'una banda, la reforestació dels prats i pastures abandonades regula els serveis de l'ecosistema, com per exemple la hidrologia, l'emmagatzematge de carboni o l'increment de l'estabilitat del sòl. De l'altra, el creixement del bosc disminueix la biodiversitat, la qualitat i quantitat de les pastures i la qualitat estètica del conjunt, transformant l'heterogeni paisatge agrari de muntanya en un paisatge homogeni dominat pel bosc. Els efectes de la reforestació s'han de tenir presents a l'hora de planificar les polítiques de gestió del territori.

Com a conclusió general, cal executar noves polítiques que esdevinguin realment eficients orientades a la potenciació i al suport de les activitats agrícoles i ramaderes tradicionals, així com permetre la participació en la pressa de decisions de tots els actors implicats en el territori per conservar el paisatge d'alta muntanya. En aquest sentit, el present model pretén esdevenir una eina que ajudi a preservar aquest patrimoni cultural i ecològic per a les generacions futures, abans que desaparegui completament.

Zusammenfassung

Ab der zweiten Hälfte des 20. Jahrhunderts wurde eine Ausweitung des Waldes in den Zonen der europäischen Berge beobachtet. Diese Transformation der alpinen Landschaft geht auf Veränderungen in der Bodennutzung zurück. Die für die Landwirtschaft am besten geeigneten Oberflächen durchlaufen einen Intensivierungsprozess, während in den Flächen die weiter von den bewohnten Ortschaften entfernt liegen oder schwerer zugänglich sind die Intensität der Bodennutzung abnimmt, sodass sie sukzessive von Büschen und Wald kolonisiert werden. Ein Großteil dieser landwirtschaftlichen Flächen besteht aus naturnah Weiden und Wiesen mit einem besonderen ökologischen und ästhetischen Wert, für welchen sie unter Naturschutz, genauer unter Kulturlandschaftsschutz, stehen.

P Systeme sind bioinspirierte Computermodelle und ermöglichen die Modellierung komplexer Ökosysteme unter Einbeziehung einer großen Anzahl von Akteuren, die sich entwickeln und untereinander und mit ihrem Umfeld interagieren. Die Entwicklung der traditionellen Kulturlandschaften wurde in zwei alpinen Regionen modelliert: In den katalanischen Hochpyrenäen und im Stubaital, in den Zentralalpen. In beiden Fällen wurden drei Simulationszenarien erarbeitet, die unterschiedliche Intensitäten der landwirtschaftlichen Aktivität berücksichtigen: (1) Fortführung der beobachteten landwirtschaftlichen Tendenzen oder Aufrechterhaltung des *status quo*, (2) signifikante und (3) sehr starke Reduzierung des Viehbestands.

Die erzielten Ergebnisse zeigen den Rückgang der traditionellen Kulturlandschaften in allen drei simulierten Zukunftszenarien und in beiden Untersuchungsgebieten. In den Pyrenäen verlieren die Flächen im Höhenbereich zwischen 1700 und 2600 m den größten Anteil der landwirtschaftlich genutzten Fläche. Die stärkste Wiederbewaldung findet zwischen 2200 und 2600 Höhenmetern statt, insbesondere auf mäßigen Hängen (≤30°). In den Alpen, ist die stärkste Reduktion der Kulturlandschaften und nachfolgende Wiederbewaldung für den Höhenbereich zwischen 1500 und 2150 m zu erwarten. Die traditionellen Kulturlandschaften der Berge entwickeln sich je nach Reduktion der Nutztiere. Die jährlichen Variationen im Ziegen-, Schaf-, Rindvieh- und Pferdbestand haben einen signifikanten Einfluss auf die Landschaftstransformation. Insbesondere Rinder sind sowohl aufgrund ihrer speziellen Nahrungsbedürfnisse, als auch aufgrund ihrer Anzahl in beiden Studiengebieten bedeutend.

Einerseits reguliert die Wiederbewaldung der aufgelassenen Wiesen und Weiden die Leistungen des Ökosystems, wie z.B. die Hydrologie, der Kohlenstoffdioxidspeicher oder die Zunahme der Bodenstabilität. Andererseits sinken mit der verstärkten Bewaldung die natürliche Biodiversitätdie Qualität und Quantität der Weiden und die ästhetische Qualität des Gesamten, da sich die heterogene Gebirgskulturlandschaft in eine homogene walddominierte Landschaft verwandelt. Die Effekte der Wiederbewaldung müssen im Landschaftsplanungspolitik berücksichtigt werden.

Als generelle Schlussfolgerung, ist auf die Notwendigkeit neuer Politiken hinzuweisen welche wirklich effizient und an der Potenzierung und Unterstützung der traditionellen landwirtschaftlichen Aktivitäten orientiert sind. Ein Beispiel wäre die Einbeziehung aller beteiligten Akteure in die Entscheidungsfindungsprozesse zur Erhaltung der Landschaften der Hochgebirge. In diesem Sinne, hofft das präsentierte Modell ein hilfreiches Werkzeug in der

Erhaltung dieses kulturellen und ökologischen Erbes für zukünftige Generationen zu sein, bevor dieses vollständig verschwindet.

Resumen

Desde la segunda mitad del siglo XX se ha observado un expansión del bosque en las zonas de montaña europeas. Este transformación del paisaje alpino está provocada por cambios en los usos del suelo. Las superficies más aptas para la agricultura y la ganadería sufren un proceso de intensificación, mientras que las superficies más alejadas de de los núcleos habitados y con una accesibilidad menor se reduce la intensidad del uso del suelo que se practica y son recolonizadas progresivamente por el matorral y el bosque. Una gran parte de estas superficies agrícolas son prados y pastos seminaturales de gran valor ecológico y estético, por lo que disponen de un determinado grado de protección.

Los P sistemas son modelos computacionales bioinspirados que permiten la modelización de ecosistemas complejos en los que un gran nombre de actores evolucionan e interactúan entre ellos y con el medio. La evolución del paisaje agrícola tradicional se ha modelizado en dos regiones alpinas: los altos Pirineos catalanes y el Valle de Stubai, en los Alpes centrales. En estas áreas de estudio se han establecido tres escenarios a simular de acuerdo a la intensidad de la actividad agrícola: (1) continuación de la tendencia ganadera observada, o mantenimiento del status quo, (2) reducción significativa y (3) muy fuerte de la carga ganadera.

Los resultados obtenidos muestran como la superficie agrícola tradicional se reduce en todos los escenarios futuros simulados y en las dos áreas de estudio. En los Pirineos, las superficies situadas entre 1700 y 2600 m de altitud son las que pierden una mayor proporción de superficie agrícola. La mayor reforestación se produce entre 2200 y 2600 m, siendo superior sobre pendientes moderadas (≤30°). En los Alpes, la perdida más importante de superficie agrícola, posteriormente reforestada, se prevé que se produzca en el rango comprendido entre 1500 y 2150 m de altitud. El paisaje cultural de montaña evoluciona a medida que se reducen los animales domésticos. Las variaciones anuales en los censos de cabras, de ovejas, de vacas y de yeguas tienen un efecto significativo en los cambios en el paisaje. No obstante, las vacas son el animal cuyo efecto tienen un peso superior, tanto por sus necesidades alimentarias como por su censo en las dos áreas de estudio.

Por un lado, la reforestación de prados y pastos abandonados regula los servicios del ecosistema, como por ejemplo la hidrología, el almacenaje de carbono o el incremento de la estabilidad del suelo. Por el otro, el crecimiento del bosque disminuye la biodiversidad, la calidad y cantidad de los pastos y la calidad estética del conjunto, transformando el heterogéneo paisaje agrario de montaña en un paisaje homogéneo dominado por el bosque. Los efectos de la reforestación han de ser tenidos en cuenta al planificar las políticas de gestión del territorio.

Como conclusión general, es necesario ejecutar nuevas políticas que sean realmente eficientes orientadas a la potenciación y al apoyo de las actividades agrarias y ganaderas tradicionales, así como permitir la participación en la toma de decisiones de todos los actores implicados en el territorio para conservar el paisaje de alta montaña. En este sentido, el presente modelo pretende ser una herramienta que ayude a preservar este patrimonio cultural y ecológico para las generaciones futuras, antes que desaparezca completamente.

Prologue

Prologue

For centuries man has inhabited the European mountain chains, establishing a balance with the environment, and using the natural resources that have been provided: pastures, firewood, food, etc. The need to increase the surfaces used to feed his animals pushed him to cut montane and subalpine forests, hence, creating semi-natural habitats of great ecological and cultural value, such as meadows and mountain pastures.

Since the mid-20th century, this situation has been changing. Due to socio-economic changes the traditional activities have been losing importance. In broad terms, crops become progressively meadows; meadows, pastures; and, finally, these remain abandoned and recolonized by forest vegetation. This situation, known as land-use and cover change (LUCC), has caused major changes in mountain regions, transforming the traditional agricultural landscape in a landscape dominated mostly by forest.

The problem is not only restricted to the agricultural and livestock sector, but has consequences for the loss of biodiversity and the modification of the ecosystem services, including important aspects as water availability, forest fires, the aesthetic perception of the traditional landscape and the loss of identity of the mountain population. Society is no stranger to this reality, reaffirming its conviction that it is essential to preserve this important cultural heritage, but is not achieving major advances so far.

The conservation of traditionally agricultural alpine surfaces is closely linked to the maintenance and promotion of mountain farming. Due to the harsh conditions, every time fewer persons work exclusively in agriculture, combining it with tourism in the best of cases or abandoning the mountain villages in the worst. Therefore, the maintenance of the agricultural population and of traditional activities is the main challenge to be achieved to ensure the preservation of the mountain landscape.

To try to reverse the current trend, it is necessary to know how mountain landscapes will evolve, allowing effective decisions and efficient management of the territory, taking into account as many involved persons as possible. In the last few years, on the one hand, the knowledge on mountain ecology has increased noticeably and, on the other hand, important advances in the field of computational modelling have been achieved. The combination of advances in these two areas allows for the construction of computational models with major potential, capable of modelling with great detail the landscape changes. Within this context, this thesis aims to create a tool to predict and analyze the future evolution of mountain landscapes in various scenarios, using a new computational modelling tool: the P systems.

It is hoped that this model can become useful conserving the ecological and cultural heritage, which comprise the fragile mountain ecosystems, allowing future generations to enjoy them before they are lost forever.

Objectives

The general objective of the thesis is to build a model with P systems, apt to identify and quantify landscape changes caused by changes in land uses and allowing future predictions. In this model are involved, on the one side, livestock and wild ungulates, and on the other, plant communities or habitats, characterized as cultural land uses. From this general objective emerge the following specific objectives:

1. To build a model with P systems that allows performing future predictions, identifying and quantifying the landscape changes in mountain areas caused by modifications in land use.

2. To apply the model in two case studies, in the Catalan Pyrenees, and in the Stubai Valley, in the Alps, to predict and assess the future evolution of the landscape over the course of 30 years in different hypothetical scenarios.

3. To know and analyze the factors that affect changes in the landscape.

4. To analyse the model's results and possible applications to land management.

For each chapter of this thesis particular objectives are specified in detail. These partial objectives complement and clarify the general aim of the present study.

Structure of the thesis

The doctorate thesis is structured in 9 chapters, each of which focuses on a particular aspect. The first two chapters introduce the theoretical framework necessary to understand the landscape changes and the basics of LUCC modelling with P systems. Afterwards, the two study areas are presented and the designing process of the model is described. Finally, the results are shown, followed by a general discussion, and the conclusions including prospects on future work.

Chapter 1. Changes in mountain landscapes

Chapter 1 is devoted to changes in mountain landscapes that are taking place in the major European mountain chains, reviewing the main existing bibliography. A special emphasis is placed on the Pyrenees and the Alps, because they are the mountain ranges considered in the case studies. Among others, the causes of the land use changes are discussed and a set of arising consequences is detailed, including ecological and societal affects. In the following, it is commented which future scenarios are expected to occur in the mountain regions and which will be used for the definition of future scenarios in the simulation. Finally, a selection of LUCC models is provided.

Chapter 2. Cellular membrane computing: the P systems

Chapter 2 is about the modelling with membranes, the so-called P systems. In the first sections the concept of natural computing, which includes P systems, is introduced, and its origin and main developed variants are explained. One of these variants are the *Population Dynamic P systems* (PDP), used in this work, which are explained in detail, as well as the basics that have been established for the design of models and for their application. Finally, main aspects that recommend the use of the PDP models for the modelling of natural ecosystems are commented.

Chapter 3. *Description of the study areas*

The study areas in which the PDP model has been applied for the study of LUCC are described: the high Catalan Pyrenees and the Stubai Valley in the central Alps (Tyrol, Austria). The description of the study area includes socio-economic characteristics, a characterization of the physical framework, the practiced uses of soil and the vegetation, and, finally, the grazers, both livestock and wild ungulates, as well as their use of alpine and subalpine pastures during the summer months.

Chapter 4: The PDP model to predict LUCC in mountain regions

In Chapter 4 it is shown step by step how the PDP model was designed. This includes, among others, the processes to model, model entries, the design of the model and the different configurations for the implementation of a complete cycle, according to the modelling protocol proposed by Colomer et al. (2013). The model presented in this chapter is a generic model, adaptable to both, the case study in the Pyrenees and in the Alps.

Chapter 5. Results for the Catalan Pyrenees and Chapter 6: Results for the Stubai Valley

Once presented the methodology to build the PDP model, it is applied to the two study areas. The structure of the two chapters of results is identical in both cases. To begin with, in the first paragraph the scope of application and the different scenarios under which the model is applied, as well as its goodness of fit are justified. In a second section the results obtained for each modelled scenario are shown. The purpose is to identify and quantify the LUCCs and to identify for each case under which conditions of slope and altitude they are produced.

Chapter 7. Analysis of results by means of response-surface models

An experiment for each study area has been designed to model the surface of response used to fit a polynomial model, with the aim of getting to know the behaviour of the model and to establish what are the variables that affect the changes in the landscape and the weight that they represent in each case.

Chapter 8. General discussion

After presenting the results obtained for each study area and their analysis, they are discussed in detail.

Chapter 9. Conclusions and future work

Finally, in the last chapter, the most important contributions, extracted after analyzing the results, are presented. Furthermore, a series of proposals to explore in future work is provided in order to improve the modelling of natural ecosystems with P systems and to increase the knowledge of the ecology of the high mountain regions.

Chapter 1. Changes in mountain landscapes

"Land-use changes are considered to be the major driving forces of change in ecosystem functions and dynamics, and in landscape pattern in Europe." (Cernusca et al., 1996).

Chapter 1

Changes in mountain landscapes

1.1. Introduction

The European mountain landscapes are undergoing a spontaneous reforestation since the second half of the 20th century. Numerous studies have analyzed landscape transformations, concluding that their main cause is related to changes in agricultural land uses; a process that is known by the abbreviation *LUCC* (*Land-use and cover change*) (Cernusca et al., 1996; Cocca et al., 2012; MacDonald et al., 2000; Mottet et al., 2006; Tasser and Tappeiner, 2002).

Land-use and landscape changes have been observed in most of the European mountain ranges, for example in the Alps (Tasser and Tappeiner, 2002; Zimmermann et al., 2010); in the Pyrenees (Garcia-Ruiz et al., 1996; Mottet et al., 2006); in Mediterranean mountains, in the Scottish Highlands and in the Carpathians (Hobbs, 2009; Hostert, 2010; Lasanta-Martínez et al., 2001). A quite obvious aspect of the land-use changes are abandonment or extensification, leading to the reforestation of erstwhile wooded zones that had been cleared to gain agricultural surface. However, changes in land use also manifest themselves in other – opposed – ways, for example as intensification, meaning an increase in the production capacity of certain surfaces

Throughout history, humans have modified their environment to adapt it to their needs. The biogeographic characteristics of mountains and the traditional land uses associated with a low intensity agriculture have created semi-natural landscapes of great ecological and cultural value (MacDonald et al., 2000). Some examples are species-rich meadows (Bolliger et al., 2011; Fillat, 2003a; Prince et al., 2012) or larch meadows and pastures in the Alps (Garbarino et al., 2011). These cultural landscapes are at risk to disappear due to changes in land use, both intensification and abandonment of agricultural activities (Ostermann, 1998). Facing a possible loss of these ecosystems, many of these habitats were put under protection. At European level, for example, a large part of the mountain landscapes are included in the annex I of the Habitats Directive (92/43/EEC) as natural habitat types of Community interest, whose conservation requires the designation of special areas of conservation. At a social or cultural level the disappearance of traditional agricultural landscapes is seen, on the one hand, as a loss of traditional cultural heritage and, on the other, as a reduction of the aesthetic perception of the landscape (MacDonald et al., 2000; Schirpke et al., 2013a, 2013b). This shows how LUCC effects go beyond the agricultural and livestock sector, modifying the multiple ecosystem services, both, from an ecological and a cultural point of view (Fillat et al., 2011; Gibon, 2005; Schirpke et al., 2013a; Tasser and Tappeiner, 2002). For the maintenance of the Alpine landscape and its floristic richness, it is essential to adopt measures supporting extensive agriculture and farming, as only this can avoid the disappearance of a world in constant transformation that fights for survival.

1.2. Land-use and cover change: The LUCC

1.2.1. LUCC's causes

The abandonment of agriculture and livestock farming began in the Europe of the mid-19th century, as a side-effect of the urbanisation processes that first began in the most industrialized European countries but soon spread to the rest of the continent (García-Ruiz and Lana-Renault, 2011; Guirado and Tulla, 2010; Siegl and Schermer, 2012).

During the 20th century, and especially pronouncedly in its second half, a series of socio-economic changes occurred, which accelerated the land-use changes in mountain areas. Some of the most notable alterations, were the introduction of the market economy, technological innovations, the application of agricultural policies, depopulation and shifts in the productive sector (García-Ruiz and Lana-Renault, 2011; Lasanta-Martínez et al., 2005; Siegl and Schermer, 2012). This phenomenon was also common in other rural zones, but its consequences have been felt with a higher intensity in the mountain areas (Zimmermann et al., 2010).

In the 1950s, the traditional self-sufficient economy, which had been typical for the Alpine regions, entered in crisis and was replaced by a market economy that destabilised the traditional agricultural system, forcing it to adapt to the new reality. The expansion of the capitalistic production model condemned many farms to abandonment or changed uses, because they were no longer competitive in this new situation (Guirado and Tulla, 2010; Lasanta-Martínez et al., 2001; Ringler, 2009; Siegl and Schermer, 2012). This led to a general reduction of the population engaged in agriculture and of the number of farms (García-Martínez et al., 2009; Tappeiner et al., 2006). Another key aspect interfering in this decline was and continues to be the lack of generational succession (Barrachina and Tulla, 2010; Bernués et al., 2011; Gibon et al., 2010). Young people do not continue with family farming due to the loss of social prestige, the lack of profitability, the working conditions and difficulties to find a partner (Valdevira, 2008). However, the drastic farm reduction has not resulted in a reduction of the livestock censuses, since the average number of animals per farm has increased (Bernués et al., 2011). The reasons for this development originate from the process of modernization and restructuring of the agricultural sector, in which nowadays only big farms are competitive enough to earn a living. (Idescat, 2009). The mechanization of agriculture and the incorporation of new techniques, prioritising intensive production, have played an essential role in the transformation of the agricultural sector, favouring some surfaces at the expense of others (García-Ruiz and Lana-Renault, 2011; MacDonald et al., 2000; Mottet et al., 2006; Siegl and Schermer, 2012). This means, for example, the selection of easily accessible areas with gentle slopes for intensive farming and, simultaneously, the extensification or abandonment of less accessible surfaces. The consequences of these processes are largely discussed in detail in the following section.

Since these years of agricultural decline, a series of European and national economic measures have been established, aimed at reviving livestock farming and agriculture in mountain areas, and at encouraging the diversification of activities, especially combining farming with tourism (Guirado and Tulla, 2010; Siegl and Schermer, 2012). Examples for measures at state and regional level, although within the European rural development policy for the years 2007-2013, are the Austrian agri-environmental programme (ÖPUL), promoting an environment-friendly extensive agricultural land use and the conservation of the countryside (Lebensministerium, 2013), and the Rural Development Programmes drawn up by different Spanish autonomous communities (MAGRAMA, 2013). Moreover, it is necessary to highlight the common agricultural policy of the European Union, better known by its acronym CAP, as it is essential in this context. Started in 1962, it provides support for measures aimed at improving the productivity, competitiveness and sustainability of agriculture (European Commission, 2013). The different states have benefited from the CAP after their accession to the European Union, Spain (1986) and Austria (1995). Due to the importance of the European subsidies for the agricultural development, both in terms of the amount of funding and regarding the established criteria that have to be satisfied, the CAP and its hypothetical changes are usually used as the basis to establish agricultural scenarios that may occur in the future.

Despite these measures to promote agriculture, the Alpine regions have chosen tourism as the best – and in many cases the only – way to develop economically. The change in the productive sector featured a reduced importance of the farming, which stopped being the predominant sector, and has led to a flow of labour towards the service sector (Lasanta Martínez et al., 2013; Tappeiner et al., 2008). This process has developed differently according to regional characteristics: for instance, with a strong depopulation in the Spanish Pyrenees, which is still evident today (Pinilla et al., 2008), or a change in the productive sector in the Federal State of Tyrol (Central Alps, Austria) (Siegl and Schermer, 2012). Large parts of the population engaged in agriculture diversified their economy in order to survive, combining, for instance, tourism with part-time livestock farming (Bernués et al., 2011; Lopez-i-Gelats et al., 2011; Tappeiner et al., 2008). The existing offer of agri-tourism, which combines the experience of daily life on a farm with tourism in contact with nature, includes Rural Tourism in Spain and *Urlaub auf dem Bauernhof* (Holidays on the farm) in Austria.

1.2.2. Land-use intensification and extensification

The transformation of the agricultural world has brought as a consequence two antagonistic but complementary processes, which are replacing the traditional cultural landscape: on the one hand, a specialized and intensive exploitation of the surfaces more suitable for agriculture and, on the other, an extensification, abandonment and subsequent spontaneous reforestation of marginal agricultural areas (Guirado and Tulla, 2010; Schneeberger et al., 2007; Tasser and Tappeiner, 2002).

The degree of intensity of the use of Alpine meadows is conditioned by the slope and by the accessibility for agricultural machinery. Tasser et al. (2002) have calculated in the Alps that in intensively used surfaces, the slope is of 18° - 28°, while surfaces with extensive use are located on sites with moderate slopes between 24° and 34°.

At the valley bottoms, the most favourable zones for agriculture, grainfields have been replaced by meadows, which have undergone a process of intensification, understood as the introduction of a large number of inputs in order to increase the fodder production per surface unit (Garcia-Ruiz et al., 1996; Siegl and Schermer, 2012; Tappeiner et al., 2006). This highly productive agriculture is characterized by a high fertilization of the surfaces, the use of irrigation, and several cuts per year (Rutherford et al., 2008; Tasser and Tappeiner, 2002). The purpose of these intensively used meadows is the production of hay to feed the animals during the winter months. Their management varies in the Alps and in the Pyrenees, because of different climatic conditions: in the Alps, characterized by a high degree of humidity, it is possible to cut 3 or 4 times per year (Tappeiner et al., 2008), while in the Pyrenees, even in the most appropriate and irrigated areas only two cuts per year are possible (Fillat, 2003b). In some cases these intensive meadows, both in the Pyrenees and in the Alps, are also used as pastures in spring and in autumn, before and after their use as meadows.

Unlike the most productive grasslands, marginal areas are characterised by difficult accessibility, often because of high slopes and long distances to the villages. Therefore, the opposite process occurs, that is to say a reduction of agricultural intensity or extensification to the point of total abandonment (Garcia-Ruiz et al., 1996; Tasser and Tappeiner, 2002). These surfaces include species-rich grasslands and mountain meadows (Chocarro and Reiné, 2008; Fillat, 2003a; Tasser and Tappeiner, 2002). The first step in the extensification process is the replacement of grain fields by meadows dedicated to the production of hay for animals, a decision provoked by the fact that the cereal production ceased to be economic and forage is required for the winter months. The second step is the conversion of meadows into pastures grazed during the summer months. Finally, the third step is characterized by the progressive reduction of the pastoral use until the final abandonment of the surface (Molinillo et al., 1997; Mottet et al., 2006).

Once an agricultural surface is abandoned, begins the colonization of the surface by woody species by means of the *secondary ecological succession*. In a first succession stage the herbaceous vegetation is replaced by shrubby vegetation, which is in the following substituted by tree vegetation, except for the surfaces above the upper limit of the forest, the so-called tree line (Améztegui et al., 2010; Gellrich et al., 2007; Tasser et al., 2007; Wallentin et al., 2008). Therefore, the abandonment of traditional economic activities has led to a transformation of the landscape in Alpine regions, substituting the heterogeneous open landscape with combinations of agricultural and forest zones, by forest dominated homogeneous landscapes (Kulakowski et al., 2011). However, this process occurs highly variably.

At the beginning of the ecological succession farming systems are affected, reducing the grazing surface. Although this grass continues to produce forage, it is no longer available for large herbivores, as the presence of shrubby vegetation impedes their access. When shrubby vegetation is covering a former agricultural area, there are only two strategies, in practice, to return to the previous situation: clearing the shrubs with machines or fire. Both methods allow to start a new process of succession dominated, at least in the early stages, by the herbaceous vegetation (Molinillo et al., 1997).

Both intensification and extensification are occurring simultaneously, but extensification is the more frequent process (Mottet et al., 2006). Rutherford et al. (2008) observed, for example, in the Alps that agricultural land is three times more likely to be abandoned than to undergo intensification. Processes of extensification and abandonment in mountain areas have been affecting more than 90% of the farmland in the Pyrenees, about 20% of the Prealps (Taillefumier and Piégay, 2003), at least 70% in the Eastern Alps (Tappeiner et al., 2003; Tasser et al., 2007) and 30% in the Carpathians (Hobbs, 2009). These high proportions of affected surface and the resulting landscape changes, provoke that extensification and abandonment are of high interest to ecologists, particularly in mountain areas.

1.3. Ecological effects of land-use changes

Land-use changes entail a large number of ecological consequences , which may affect the multiple ecosystem services (Fillat et al., 2011; Lamarque et al., 2011; Schirpke et al., 2013a). Some of the most important impacts regard diversity, biogeochemical cycles, hydrology and natural hazards.

Diversity refers both to species and to landscapes. Traditional agricultural landscapes feature a greater biodiversity and floristic richness than abandoned and intensified zones (Bolliger et al., 2011; Fischer et al., 2008; MacDonald et al., 2000; Tasser and Tappeiner, 2002; Tasser et al., 2005). Although most studies on biodiversity have focused on plant species, animals are affected, too. Regarding birds, observations show that abandonment and reforestation favour forest species at the expense of those adapted to agricultural open spaces, and that the most affected species are migratory birds, for being less adaptable to changes (Fonderflick et al., 2010; Marriott et al., 2004; Sirami et al., 2008). Other groups, for example wild ungulates, benefit from abandonment and increasing forest surfaces, expanding their populations to numbers that seemed out of reach not long ago (Herrero et al., 2008). Concerning landscape, both intensification and extensification lead to a homogenization and a loss of the traditional agricultural landscapes, which are characterized by being composed of a mosaic of meadows and pastures with tree or scrub margins (Fischer et al., 2008; Tasser et al., 2007, 2005).

The LUCC affect biogeochemical cycles in different ways, depending on whether there intensification or abandonment take place. For example, intensification includes an increased use of fertilizer and pesticides, while abandonment is accompanied by less contamination caused by these products (Tasser and Tappeiner, 2002; Tasser et al., 2007). Moreover, land uses are one of the main factors determining the carbon flow between terrestrial biosphere and atmosphere (Hiltbrunner et al., 2013; Schmitt et al., 2010). Forest has a carbon storage capacity ten times higher than pastures and alpine scrubs, so that reforestation means an increase in the carbon fixation (Bolliger et al., 2008; Hiltbrunner et al., 2013; Tappeiner et al., 2008). Furthermore, forest functions also a storage for organic carbon in the soil, featuring a capacity much larger than the rest of surfaces (Hiltbrunner et al., 2013). In addition, it is important to consider that in abandonment processes, the increase of organic material produced, which needs to be decomposed provokes a long-term soil acidification, which leads in turn to vegetation composition changes (Tasser et al., 2005).

With regard to the hydrologic balance, the soil's water retention capacity and the degree of surface runoff are modified. Similar soils show in situations of intensive land use a greater capacity to store water and facilitate more water to plants than when land-use intensity is reduced (Tasser et al., 2005). Forests, meadows and shrubland transpire significantly more water than other land uses, such as pastures. This greater evapotranspiration reduces the runoff and sediment transport (Leitinger et al., 2010; Nadal-Romero et al., 2013; Tasser et al., 2005). The reduction of runoff, however, can cause problems in drier regions, for example at the south side of the Pyrenees, as the water available for human consumption or for irrigation would be reduced (López-Moreno et al., 2013, 2006).

Finally, due to these and other processes, LUCC play an important role in the prevention of certain natural hazards. On the one hand, the risk of soil erosion, landslides, snow gliding and the formation of avalanches is lower when a territory is grazed or mowed than during the initial stages of abandonment and of intensification. However, these hazards are considerably minimised with the development of tree and shrub communities, so that abandonment lowers the risk of natural hazards in the long term (García-Ruiz and Lana-Renault, 2011; Tasser et al., 2005, 2003). On the other hand, bigger forest surfaces, contain a higher risk of forest fires, especially when vast zones are covered by a homogeneous forest (García-Ruiz and Lana-Renault, 2011; Lasanta-Martínez et al., 2005). This hazard is more important in mountains with Mediterranean climate, such as the Pyrenees, and are rather rare in the Alps due to the higher humidity.

1.4. "What landscape do we want?" Social perceptions of landscape changes

Another important aspect regarding landscapes is their attractiveness for tourism (Hunziker et al., 2008; Schirpke et al., 2013b), being an important source of income for the population, but also its perception by the inhabitants themselves, as it may influence, for example, their landscape management or their decision to stay in the area or not. This relevance has led to the emergence of works studying the aesthetic quality of mountain regions and the society's perception of landscape changes (Bacher et al., 2012; Hunziker et al., 2008; Kianicka et al., 2006; Schirpke et al., 2013b). On the whole, the reduction or disappearance of traditional agricultural landscapes is perceived as something negative. Although studies find usually a clear preference towards traditional agricultural landscapes, no special rejection of extreme landscapes, highly intensified or characterized by a strong farming abandonment and forest domination, was observed (Bacher et al., 2012; Hunziker et al., 2008).

When comparing different cultural or social groups, the perceptions can vary significantly. For instance, Hunziker et al. (2008) found in their work interrogating three different social groups in the Swiss Alps, that tourists value the current landscape more positively than local inhabitants and than the general Swiss public, while the strongly reforested scenarios receive the highest acceptance from the general Swiss public, followed by tourists and local inhabitants. Experts in landscapes and decision-makers perceive the landscape evolution in a different way (Hunziker et al., 2008). They have a clear preference for a return to the cultural agricultural landscape and see the intensification and reforestation much more negatively than the rest. Moreover, other studies have shown that the view of the population who is not professionally engaged in agriculture is different from those who are engaged in agricultural activities. The first have generally a more aesthetic and recreational view, while the latter represent a more functional perspective (Steinbacher et al., 2012) arguing against reforestation, because it reduces the grazing surface (Fernández-Giménez and Fillat, 2012). Regarding different cultural groups, Bacher et al. (Bacher et al., 2012) observed in the bilingual region of South Tyrol (Italy) that Italian-speaking interviewees were less critical with intensification than German speakers.

Given these diverse perceptions, it is important to search for compromises, considering the views of different social groups, when designing future policies. Only when bearing the different visual perceptions in mind, solutions satisfying the needs of all parties can be found.

1.5. Future scenarios

The analysis of what has happened in the past and perceptions of what could happen in the near future, can help to predict landscape changes that are likely to happen in the next years. The future scenarios presented in the following are based on the predictions of different experts and stakeholders on the basis of socio-economic changes. Mountain areas are directly or indirectly conditioned by agricultural subsidies or other types of rural funding to maintain the current land use (Bayfield et al., 2008). An important determining factor for agriculture in the European Union is the so-called Common Agricultural Policy (CAP). The revision of stakeholder predictions regarding the future of European funding for agriculture, resulted in the definition of four main possible future scenarios: (1) Maintenance of the current situation, also called *status quo* scenario; (2) reduction of the subventions for livestock farming and agriculture; (3) liberalisation of the agricultural sector; and (4) enhancements of rural diversification (Bayfield et al., 2008; Renwick et al., 2013; Soliva et al., 2008).

The first scenario, the maintenance of the *status quo*, corresponds with the continuation of European area-based payments received from 2004 to 2013, combined with limited support for rural development and rural planning restrictions (Bayfield et al., 2008). In this scenario the agricultural activity and intensity reduce gradually, continuing the recent trend of last decades. This progressive abandonment of traditional practices is associated with a moderate loss of agricultural land uses and of traditional agricultural habitats.

The second hypothetical scenario describes what would be the result of a rapid decline of European area-based payments. This reduction of agricultural subsidies is partly compensated with funding for landscape management with good cultural or environmental practices, without modifying rural planning restrictions (Bayfield et al., 2008). These additional payments could be directed, for example, to the reduction of fertilizers or the conservation of biodiversity by means of grazing and mowing. This situation would produce a strong decrease of the agricultural intensity and, hence, an abandonment of traditional cultural practices. In this scenario big parts of the extensive agricultural area would be recolonized by scrubland and forest.

The scenario defined as *liberalisation* assumes the implementation of recommendations articulated by the World Trade Organization (*WTO*) regarding market liberalisation: new limitations for internal help, reduction of taxes regulating the access to the European market, elimination of exportation subsidies, free access to European markets for the least developed countries and low taxes for selected products. It is assumed that such a liberalisation of the European agriculture would result in the abandonment of a significant part of the agricultural and its colonization by woody species (Renwick et al., 2013; Soliva et al., 2008).

Finally, the fourth future scenario contemplated by stakeholders takes the support of rural development through the diversification of uses into account. This scenario considers the continuation of area-based payments, as in the *status quo* scenario, accompanied by increased funding for rural development and a reduction of restrictions on rural planning (Bayfield et al., 2008).

Although these scenarios were described separately, combinations are possible. For instance, Renwick et al. (2013) propose a scenario in which a reduction of European funding for agriculture (scenario 2) is combined with market liberalisation (scenario 3).

1.6. LUCC modelling

In recent years, the acquisition of knowledge about the causes and consequences of LUCC has originated an outstanding interest in the modelling of these processes. Thus, a large number of models have been developed, using different techniques and approaches, such as stochastic models, statistical models, classification tree modelling, spatial models, etc. (Gellrich et al., 2007; Monteiro et al., 2011; Rutherford et al., 2008; Schirpke et al., 2012; Taverna et al., 2004). However, agent-based models (ABM) are the most commonly used in land-use literature, due to their potential to incorporate the influence of human decisions in the environment in a spatially explicit way (Matthews et al., 2007; Parker et al., 2003). Some examples of agent-based modelling (ABM) applied to LUCC are the publications by Castella and Verbung (2007), Gibon et al. (2010), Valbuena et al. (2010), Bone et al. (2011) and Sylvestre et al. (2013).

Despite the LUCC great impact on mountain areas, only few of the published models have been employed in mountain case studies. Regarding the Alps the following works are noteworthy: Taillefumier and Piégay (2003) in the French Prealps; Gellrich et al. (2007) and Rutherford et al. (2008) in Switzerland; Monteiro et al. (2011) in low areas of the Italian Alps, and Schirpke et al. (2012) in the Austrian Central Alps. In the Pyrenees, on the contrary, the number of applied models is not so extensive. In this case the works of Mottet et al. (2006) and of Gibon et al. (2010) on the northern side of the French Pyrenees can be noted. Examples of models developed and applied to the LUCC study in other mountain regions of the world are the models of Castella et al. (2007) and of Castella and Verbung (2007) in Vietnam.

After having seen how important the effects of land abandonment are for the high mountain landscapes, the development of a powerful tool to forecast their evolution is essential, especially in the case of the Pyrenees, where works of this type are almost non-existent. The work at hand wishes to contribute to this aim, applying P systems to LUCC modelling. Two case studies help to test the potentials of P systems in two European mountain chains: the high Pyrenees (Catalonia, Spain) and the Stubai Valley in the central Alps (Tyrol, Austria).

Chapter 2. Cellular membrane computing: the P systems

"We introduce a new computability model, of a distributed parallel type, based on the notion of a membrane structure." (Păun, 2000).

Chapter 2

Cellular membrane computing: the P systems

2.1. The ecological computational modelling

Ecological modelling, that is the modelling of living organisms and their relationships with the environment, is a modelling branch that has been receiving in the last years a special attention, thanks to its usefulness for the resolution of problems and as a tool to increase the knowledge about how nature is functioning (Jorgensen, 2009).

Modelling entails a simplification of reality in order to create a representation that helps to improve the knowledge of the processes under study. However, models never provide all of the features of the real system, but a part of its complexity, since, otherwise, they would be the real system itself. It is, hence, crucial that the model contemplates the characteristics that are essential in the context of the scientific problem to be solved. The models provide overviews of problems and systems that are superior in comparison with other methods, such as statistical treatments of observations, at least when the models show a high potential for including the most relevant theoretically acquired knowledge (Jorgensen, 2009).

The modelling of a natural ecosystem is a very complex process, which includes a large number of variables and internal interactions. As the complication of the system model or the degree of detail of reality increases, increases simultaneously the complexity of the model. High complexity has been in the past the main limitation in the design of models, as very powerful computers were required to execute them, using existing modelling techniques, such as differential equations.

In the last years two trends have been evidenced, which have enabled the development of modelling techniques. On the one hand, the power and the technical characteristics of computers have increased a lot, reducing many of the limitations that existed in the past. On the other hand, a large amount of scientific information, obtained with experimental methods, became available for the use in the field of ecological modelling. These two situations together have led to the emergence of new modelling tools based on new paradigms different from the techniques that can be called *classics*. The increased potential of computer equipment has produced a great proliferation of different types of more powerful models, able to model complex processes, with large amounts of involved information. In this new context the computational modelling has developed.

Computational modelling is very successful in contributing to the better understanding of complex biological behaviour, being considered an emerging science (Codling and Dumbrell, 2013; Fisher and Henzinger, 2007; Petrovskii and Petrovskaya, 2012). A computational model is a formal model, the semantics of which are operational, that is to say, that the model prescribes a series of steps or instructions that can be executed by an abstract machine, so that it can be implemented on a real computer. The computational models are created by means of computer programs, written in a specific programming language. The basic entity of computational models is known as the *state machine*, which interconnects different states or configurations of the system. The conditions under which a state is transformed into another are specified by means of algorithms. In other words, the states of an ecosystem may evolve into other under the control of a set of rules. The computational models can reach a large number of states in a non-linear and non-deterministic way, which is not possible when using mathematical models. The efficiency with which computers can execute instructions, exceeds their ability to solve differential equations, therefore computers are ideal for the execution of very complex computational models (Fisher and Henzinger, 2007).

Unlike mathematical models, which are defined as quantitative models because of the quantitative relations among variables, computational models are considered to be qualitative. This alternative is an advantage with respect to the first, in cases in which the relationships of quantities are unknown, in which different variables are involved, and in which the variables change over time under certain conditions. This is because computational models do not need to specify exact quantities, as they work based on from the knowledge of the carried out processes and their interrelationships. Thus, the computational models can be useful when not all the details of a system are known, as long as the behaviour of processes can be defined qualitatively in a robust way (Fisher and Henzinger, 2007).

Computational models have the ability to check and to compare hypotheses. Their stochastic and their non-deterministic properties enable the achievement of results comparable with experimentally obtained data. When executing a computational model two situations in which the results do not adjust to reality can occur: On the one hand, the case may be that the model cannot reproduce all the possible experimental observations, a situation in which this should be revised or improved. On the other hand, if the computational model provides outputs that disagree with experimental data, the hypothesis represented by the model is wrong and should be restricted, so that the model does not produce outcomes that are not supported by real data (Fisher and Henzinger, 2007).

It is important to keep in mind that computational models do not substitute classic models, and that depending on the purpose of the model the most appropriate option should be chosen for each situation. Sometimes models combining both types are used, the so-called hybrid models, in order to benefit from the advantages of both approaches in the same model.

Computational models require, just like the rest of models, a systematic validation to prove that the model is acceptable for the intended use. Many different validation methods exist, and the selection of one should correspond with the purpose of the model, the criteria the model must comply to be accepted and the context in which it is applied. Although, no universal standards for the establishment of criteria exist, researchers generally performs a test based on the comparison of the outcomes obtained in the simulation with real data observed (Bousquet and Le Page, 2004; Rykiel Jr., 1996).

A weak point of computational models is the impossibility to carry out a mathematical check of the obtained results. However, techniques and methods have been developed to increase the credibility of the models. These include the comparison of results obtained with computational models with the outputs from other types of models, for example differential equations (Bottis, Grodzinsky et al. 2010).

The main challenge computational modelling faces in the ecological field is to approximate the models to the end users, so that they are easily accessible for biologists and ecologists to develop their experiments. Unlike mathematical or statistical models, computational models neither have a formal construction or standards nor are they easily interpretable, which complicates their use by researchers (Fisher and Henzinger, 2007; Petrovskii and Petrovskaya, 2012).

2.2. Cellular membrane computing

The main purpose of the discipline of natural computing is the study and the simulation of dynamic processes, which occur in nature and can be interpreted as calculation procedures. The most characteristic aspect of natural computing is the fact of being inspired by nature itself, attempting to imitate natural phenomena in order to solve complex problems (Díaz Pernil and Pérez Jiménez, 2008; Pérez-Hurtado, 2010).

Natural computing is an alternative to a computing that can be called classic. It pursues research into new paradigms in order to provide an effective solution to the limitations of conventional models (Díaz Pernil and Pérez Jiménez, 2008). Within the context of natural computing, several models have been developed, attempting to emulate processes occurring in nature. Traditional bioinspired branches of natural computing are genetic algorithms, developed by Holland in 1975, and neural networks, introduced by McCulloch and Pitts in 1943; a more recent branch of natural computing is molecular or DNA computing, developed in the work of Adleman in 1994 (Păun, 2006).

However, nature does not only operate on neural or genetic level, but also at cellular level. Biological non-trivial systems are a construction, in which an intricate flow of materials and information takes place, which can be interpreted as a computational process. Following these premises, in 1998 appeared a new branch of natural computation: *Cellular membrane computing*, inspired by the structure and functioning of cells of living organisms (Păun, 2000). Membrane Computing progression has been very quick, so that the *Institute for Scientific Information* (ISI, USA) designated it in October 2003 as *Fast Emerging Research* within the area of *Computer Science* (Păun, 2010).

The cell is the morphological and functional unit of living organisms. Along general lines, cells are made up of an outer membrane, the cell membrane, which delimitates an interior space, the cytoplasm. Within the cytoplasm exist a set of cellular structures called organelles, including the nucleus, which contains the genetic material (DNA). Some of these organelles have a double membrane system, such as the mitochondria and the plastids (e.g. the chloroplasts). Other organelles, such as the endoplasmic reticulum, lysosomes, perixomes, vacuoles or the dictiosomes or Golgi apparatus are wrapped only by one membrane. Finally, there are other organelles without membranes, for example, the ribosomes and the cytoskeleton. The main feature of biological cell membranes is that they do not generate watertight compartments, allowing instead the flow of certain chemical substances, sometimes selectively or unidirectional. So the cell can be seen as a set of permeable membranes, delimiting spaces in which organelles and chemical substances are located, which are able to evolve according to specific membrane reactions. In figure 1 the inside of a eukaryotic standard cell is displayed, in this case a plant cell, which shows the structure that inspired the natural computing with membranes.

As for processes, cells of living organisms are able to perform a large set of parallel processes in perfect synchronization, an aspect that becomes an interesting source of inspiration when it comes to the modelling of complex problems. The behaviour of the cell can be considered as a non-trivial and non-predictable machine, which develops a certain calculation process. From the biological point of view, the cell performs, through hierarchical membrane distribution, a flow and alteration of chemical products that are processed within the cell itself.

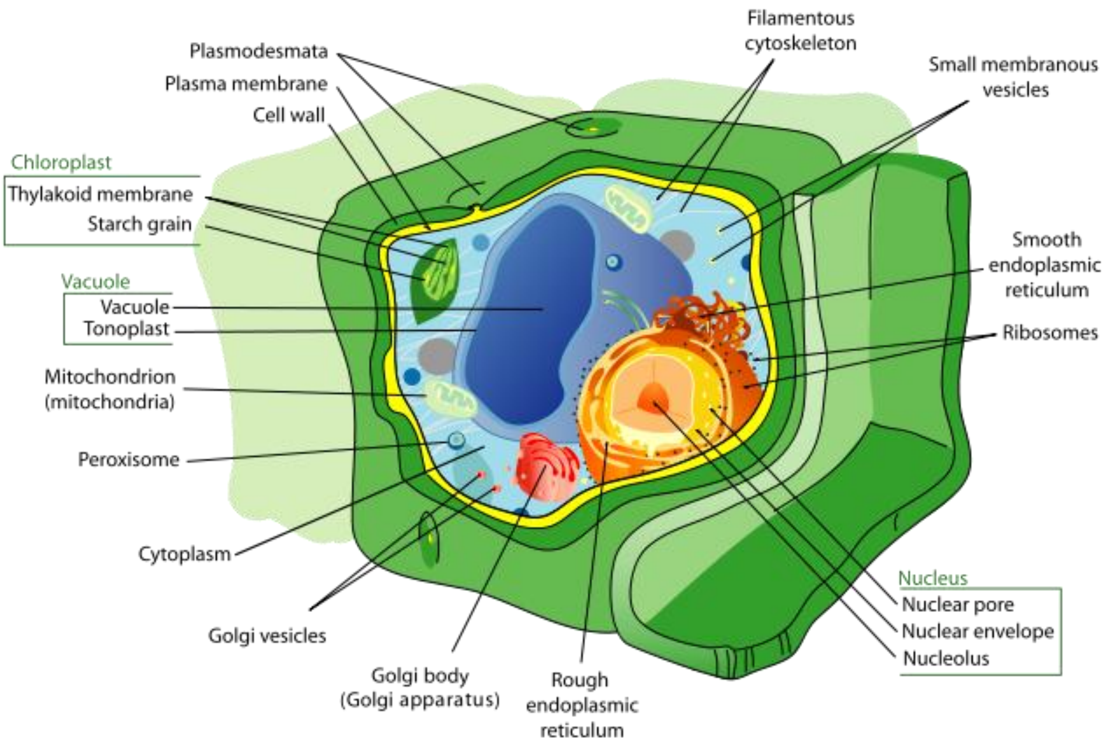


Figure 1: Eukaryotic plant cell. The cell contains a set of organelles, some of which are delimited by different types of membranes, evolving according to a series of chemical reactions. (Image of public domain)

Analogous to the cell, the basic components of P systems are (1) the membrane structure, forming compartments where (2) the multisets of objects evolve according to (3) biochemistry-inspired rules (Păun, 2000). The membranes are organized hierarchically within an outer membrane, called *skin membrane*. Multisets of objects are located within the regions defined by the membranes; these objects can appear repeatedly within the same multiset and they can evolve and move through membranes by means of evolution rules, just like real cell organelles.

Păun (2000) called the set of membranes and objects s*uper-cell*. This cell has been described by means of a Venn diagram, in which the membranes and the objects are represented, although, in the case of objects, possible multiplicities have to be considered. The super-cell, or simply *cell*, is represented graphically as a set of rectangles, which refer to the different cell-like membranes, being the outermost rectangle the representation of the skin membrane. The membranes that do not contain any further membranes are called *elementary membranes*. All the membranes have a label that identifies them. A tree diagram represents the hierarchical membrane structure of the cell. The compartments delimited by membranes are *regions*; the multisets of objects, which are called *content*, can be located in these regions. Finally, the space surrounding the cell is known as *environment* (Figure 2).

A computing device that considers the contents' possibilities to evolve is called P systems, in reference to its creator (Păun, 2000).

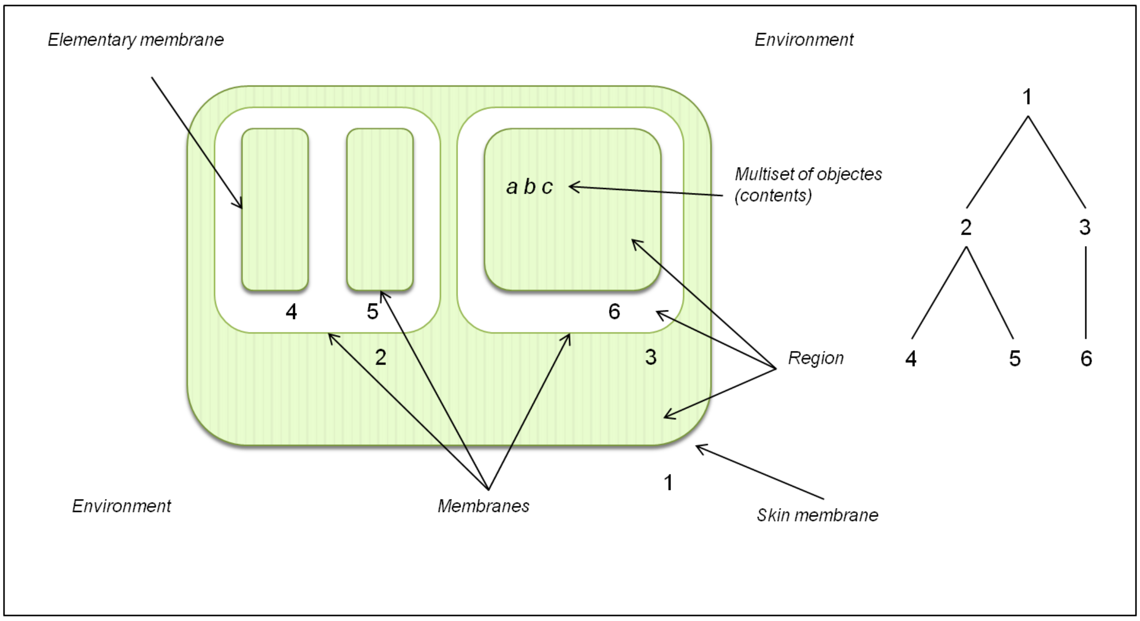


Figure 2: Membrane structure of the cell membranes and the associated tree describing the membrane structure. (Own elaboration)

2.3. Transition P systems

Transition P systems are computational devices of a distributed parallel type and were introduced for the cellular membrane computing in 1998 (Păun, 2000). Being the first described P systems, they are the basis of all later developed variants. They are distributed and parallel systems, because the computation is carried out by means of a set of components that do not depend on each other.

The basic feature of this computational model with membranes is the possibility of the objects, placed in the regions, to evolve according to certain rules. In Transition P systems the evolution rules are hierarchically arranged in a relationship of priorities. Thus, objects can transform into other objects, disappear and dissolve the membrane in which they are placed or move between adjacent regions, crossing the membranes. In this case, the membranes are abstract elements with two main functions: separating objects and serving as communication channels. These transition systems are defined below.

The membrane structure is defined as a string of parentheses, arranged within a single pair of external parentheses that correspond with the skin membrane. For example, the cell in figure 2 contains 6 membranes. Of these 6 membranes, the one identified with the number 1 corresponds to the skin, containing the membranes 2 and 3, and these, in turn, comprise the elementary membranes number 4, 5 and 6. The chain of parentheses identifying this structure is as follows:

$$\mu = [[[\quad]_4[\quad]_5]_2[[\quad]_6]_3]_1$$

The number of membranes is the *degree* of the membrane structure, while the height of the tree associated with the structure is called *depth*. In the example (Figure 2) the cell has a membrane structure of degree 6 and a depth of 3.

The transition P Systems have the following structure (Păun, 2000):

$$\Pi = (V, \mu, w_1, \dots, w_n, (R_1, \rho_1), \dots, (R_n, \rho_n), i_0)$$

Where:

- V is an alphabet, its elements are called objects;
- $\mu, n \geq 1$, is a membrane structure of degree n. All the membranes of μ are unequivocally labelled using natural numbers, from 1 to n;
- $w_i, 1 \leq i \leq n$, are strings from V that represent multisets over V associated with the regions 1,2,3,...,n of μ. These multisets can be empty, in this case they are represented as λ;
- $R_i, 1 \leq i \leq n$, are finite sets of evolution rules over V associated with the regions 1,2,3,...,n of μ; ρ_i is a partial order relation over $R_i, 1 \leq i \leq n$ that specifies a priority relation among rules of R_i. An evolution rule is a pair (u, v), which are usually written in the form $u \rightarrow v$, where u is a string over V and $v = v'$ or $v = v'\delta$, where v' is a string and δ is a special symbol not in V, which allows to dissolve the membranes;
- i_0 is a number between 1 and n which specifies the output membrane of Π.

The components μ and $(w_i), \dots, (w_n)$ of a P system define the cell. However, the graphical representation of the cell, in which the rules are applied in each region, is clearer than the symbolic description (Figure 2).

The distribution of objects within membranes at any given time is called *configuration*. The initial configuration is constituted by the components $\mu, w_1, \dots, w_n, (R_1, \rho_1), \dots, (R_n, \rho_n)$. In each configuration all possible rules are applied, causing its transformation; a phenomenon called *transition*. Generally, any sequence of type $\mu', w'_{i_1}, \dots, w'_{i_k}, (R_{i_1}, \rho_{i_1}), \dots, (R_{i_k}, \rho_{i_k})$ is called *configuration of* Π. Where μ' is the membrane structure obtained by removing from μ all membranes different from $i_1, \dots, i_k$, and where $m(w'_j)$ are multisets over $V, 1 \leq j \leq k$ inside membrane m, and $\{i_1, \dots, i_k\}$. The steps of transition are given in a non-deterministic way, that is to say that a configuration of the system can have more than one following configurations. The P systems can use *catalysts*, objects which are present in the rules but are not modified by their application, which allow the execution of a certain rule (Păun, 2000).

This computational model implements a parallelism on two basic levels: on a first level each membrane applies its own rules in parallel to its content producing new objects and enabling their communication with adjacent membranes; on a second level all the membranes perform this operation in parallel, i.e. simultaneously, without any kind of interference from operations occurring in the other membranes. The application of the rules must be maximal, in the sense that the rules are applied as many times as possible, until there is no object left inside the membranes that has not evolved yet and that could activate any of the rules associated with the membrane (Díaz Pernil and Pérez Jiménez, 2008).

The synchronization of the system is obtained following the assumption of the existence of an internal universal clock. In other words, the same clock governs in all parts of the system. At each moment, the multisets of rules are applied in parallel and non-deterministically to each of the membranes (Păun, 2000).

A computation consists of a set of configurations that succeed one another until there is no object left, susceptible to evolve. After the computing the results or outputs are codified in the number of objects placed in certain membrane.

2.4. Variants of P systems

Since the introduction of transition P systems by Păun in 1998, a large number of studies focusing on cellular membrane systems have emerged, leading to the development of a series of variants. The aim of these variants is, on the one hand to obtain a greater efficiency in solving complex computational problems and, on the other hand, to achieve a better approximation to the real biological models in which they are inspired (Díaz Pernil and Pérez Jiménez, 2008). Currently there are three main types of P systems: (1) cell-like P systems, (2) tissue-like P systems, and (3) neural-like P systems (Păun, 2010).

2.4.1. Cell-like P systems

These P systems imitate the eukaryotic cell and are, just as the first introduced P systems described above (Păun, 2000), formed by a membrane structure, multisets of objects and evolution rules. Among the variants of cell-like P systems stick out the following:

- P Systems that use strings of a specific alphabet as the basic objects of the model, such as molecules of DNA, RNA, or proteins located inside some membranes, instead of atomic objects, symbols of the alphabet without internal structure (Díaz Pernil and Pérez Jiménez, 2008).
- P systems that only allow communication among membranes, but not the generation or evolution of objects that cross the same, for this purpose new *symport and antiport* rules are used. These systems have rules that allow only the movement of objects through the membranes (Păun and Păun, 2002).
- P Systems with a stochastic type semantics that are suitable for the simulation of biological models (Díaz Pernil and Pérez Jiménez, 2008). These varieties can capture the discrete character of the components of the cellular systems and their inherent randomness, using strategies based on the algorithm of Gillespie.
- P systems that use pre-computed resources, i.e. resources that have been previously calculated. In these cases it is not important to know how they have been calculated, but how they are activated to intervene in the system computation (Díaz Pernil and Pérez Jiménez, 2008).
- P systems that allow the possibility to dissolve, create or duplicate (split) membranes, and or the use of catalysts. In this group are found *P systems with polarized membranes* (Păun, 1999a) and *P systems with active membranes* (Păun, 1999b).
- *Conformon P systems* work with a new element type, called conformon. Conformons are defined as an ordered pair of name (information) and value (energy). The interaction between two conformons is modelled as the passage of whole or a part of

the value from one name-value pair to another pair. Conformon P systems were developed by Frisco (2004).

- The *Population dynamics P systems*, probabilistic P systems with active membranes, which allow the existence of multiple environments (Colomer et al., 2013). These models are discussed in detail in subsequent sections of this chapter (Section 2.5).

2.4.2. Tissue-like P systems

Tissue-like P systems are inspired by the cellular organisation in tissues. They do not represent, hence, a single cell, but a set of cells organised in the nodes of an arbitrary graph. They were introduced by Martín-Vide et al. (2002).

In tissue-like P systems several cells, each with only one membrane, are freely placed and evolve in a common environment. Both cells and environment may contain multisets of objects. In this variant, cells are connected with each other and with the environment through communication channels. Certain cells can communicate directly and all cells can communicate through the environment. The communication is produced by means of antiport and symport rules (Díaz Pernil and Pérez Jiménez, 2008; Păun, 2010, 2006).

2.4.3. Neural-like P systems

Neural-like P systems represent a step forward in P systems, enlarging the model of tissue-like P systems. They consider more complex cells, moving the states from the channels between cells to cells themselves. Neural-like P systems aim to capture the intricate structure of neural networks, in other words the way neurons are linked and cooperate in the human brain (Păun, 2006).

At the moment, two types of neural-like P systems have been developed: one is similar to tissue-like P systems and the other is known under the name of *spiking neural P systems.* The former represents a population of interlinked cells, which have - in contrast to the tissue-like P systems - each a state controlling their evolution (Păun, 2010, 2006). The second type, *Spiking neural P systems,* was introduced by Ionescu et al. (2006). This variety incorporates the idea of working with unique objects, called spikes, in membrane modelling. Spikes can encode information through time between consecutive pulses (spikes), sent to the environment through a membrane (Díaz Pernil and Pérez Jiménez, 2008; Păun, 2010).

2.5. The Population dynamics P systems PDP

The *Population Dynamics P Systems (PDP),* also known as *Multi-environment probabilistic P Systems with active membranes,* are a variant of P systems that has been successfully applied in the simulation of ecosystems (Colomer et al., 2014, 2013; Margalida et al., 2011). As their name indicates they are probabilistic P systems, that is to say that their rules are associated with probabilities. They contain active membranes and can be formed by multiple environments, which communicate.

PDP models are able to treat with relative facility complex problems, considered to be impossible to solve with models based on differential equations, and can also simplify the modelling of problems treated with differential equations (Colomer et al., 2013).

PDP systems are composed of one or a set of environments, each of which contain a cell, a set of hierarchical arranged membranes forming the cell structure, a multiset of objects located within the membranes and, finally, the set of evolution rules that enable the evolution of the objects (Colomer et al., 2013; Margalida and Colomer, 2012). Figure 3 displays the graphical representation of the cell, the hierarchical structure of membranes and its analytical representation.

The environment can be defined as the space in which a single cell is located. PDP systems are formed by a set of environments with identical structures and with a series of relationships between them, forming a network structure.

The membranes, organised hierarchically, constitute the structures that form each cell. The membranes are hierarchically arranged in a tree structure. The membranes that contain other membranes are called *father membranes* and the inner membranes *daughter membranes*. Each is identified by a label and is electrically charged (positive, negative - or neutral 0). All cells of the system must have the same membrane structure.

The PDP systems have a work alphabet that represents *the multisets of objects*. Depending on the reality of the modelled ecosystem that is represented, two types of objects can be differentiated: those associated with the agents forming part of the model and those associated with the processes that determine their evolution and synchronization. The objects may be located in the areas defined by the membranes or outside, in the environment.

The *evolution rules* of PDP can be of two different types, depending on whether these apply to the cell or to the environment. On the one hand, the rules for the cells determine the evolution of objects within the cell, and on the other hand the rules for the environment are used to specify how objects can move from one environment to another, to generate variables correlated with the environments or to generate objects whose multiplicity depends on the environment.

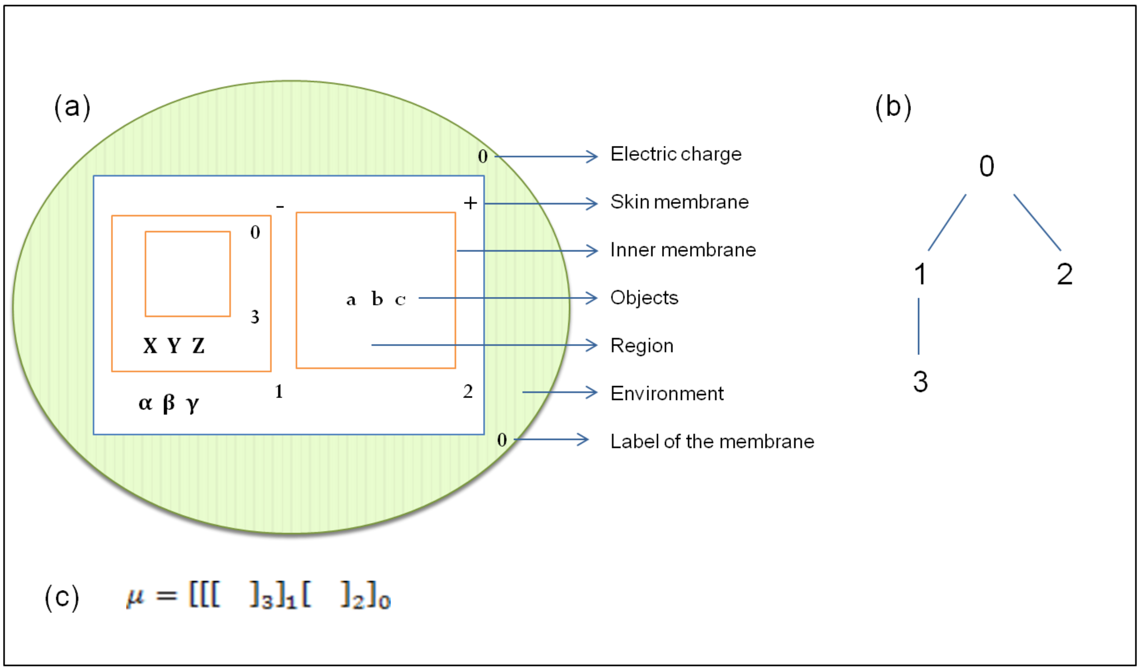


Figure 3: PDP systems structure. a) Representation and components of the cell; b) Representation of the membrane structure using a tree diagram; c) Analytical representation of the membrane structure. Adapted from Colomer et al. (2006).

The evolution rules are mathematical expressions, which are abstractions of the interactions that occur in real systems. These expressions feature two sides, a left-hand side, where objects and membranes are found before applying the rules and a right-hand side where the multisets of objects and membranes appear after the application. In the cells of P systems the rules have the following syntax:

$$r \equiv u[v]_i^{\alpha} \xrightarrow{fr} u'[v']_i^{\alpha'} \qquad \text{Equation 1}$$

Where fr is the probability that the rule is executed, which can be expressed as a constant or as a mathematical expression. If the probability is a constant of value 1, it can be omitted. In the PDP systems, the sum of the probabilities of all the rules that share the same left-hand side must sum 1. In the case of equation 1, we have a multiset v within a membrane with the label i, with an electric charge α, and a multiset u inside the father membrane. After the application of the evolution rule with a probability fr, the multisets u and v are converted into u' and v' respectively, and the polarization of the membrane changes from α to α'.

Furthermore, there are the so-called *environment rules*, which run in the environment, outside of the cell. This type of rules allows communication between the different environments of the system. When an object leaves the skin membrane, it can evolve inside the environment according to the environment rules. The syntax for this type of rules is as follows:

$$r \equiv (x)_{e_j} \xrightarrow{p(r)} (y_1)_{e_{j1}} \dots (y_h)_{e_{jh}} \qquad \text{Equation 2}$$

The multiset of objects x inside the environment e_1 moves to environments e_{j1} … e_{jh}, turning into the objects y_1 … y_h. The function $p(r)$ indicates the probability of executing this rule.

All possible evolution rules apply in a maximal way whenever the conditions for their application are given, allowing the evolution of the P systems and changes in their configuration. The different configurations are represented as multisets of objects placed in regions, which are delimited by membranes. Among the various configurations it is necessary to highlight the initial configuration, that is to say the configuration at the very beginning of the simulation process, in which the objects are exactly where the designer introduced them. When the computing process is repeated, each repetition is called a *cycle* and the last configuration of a cycle serves as initial configuration for the next (Figure 4).

A set of rules that describes one or several processes is called *module*. The modular structure enables the introduction of new processes to be modelled, without major changes in the rest of the model.

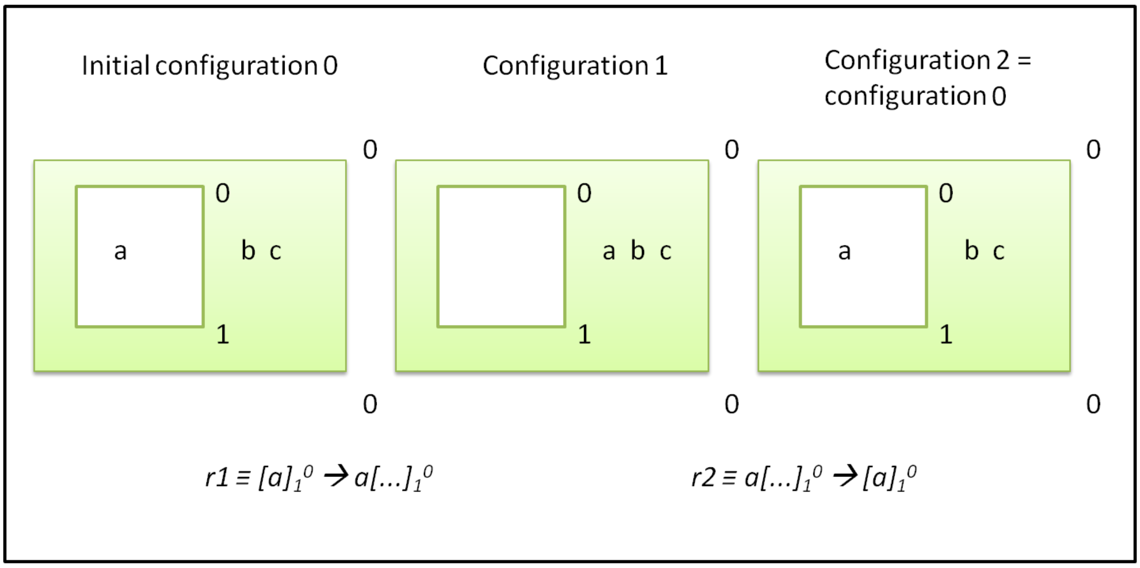


Figure 4: Example of the application of two evolution rules in a cycle that repeats itself. In the initial configuration only the rule 1 can apply, for which the object a, taking into account its multiplicities, passes from the membrane 1 to 2, leading, hence, to a new configuration, number 1. In configuration 1 the second rule can be applied, through which, the object returns to the membrane 1, obtaining configuration 2, which, in this instance, is identical to the initial configuration. At this point the cycle would be finished and a new one would begin, since evolution rule number 1 would apply again. New cycles start as long as rules can be applied, so that the simulation finishes when no more rules can be applied or, in other words, when no more objects are left to evolve. (Own elaboration)

2.6. Modelling with PDP models

The P systems in general and the PDP in particular have a complex structure, and are, hence, more difficult to describe than other modelling tools, as for example the differential equations, which are described by means of analytical expressions. This difficulty has made it necessary to create criteria for establishing the bases for the design phase and for the application of PDP models. Within this context, Colomer et al. (2013) published a protocol for modelling with PDP models, proposing 7 steps to follow. While the first four steps are the same in other model types, the rest are specific to modelling with PDP systems. The proposed steps, which have also been applied in this thesis, are the following (Colomer et al., 2013):

Step 1: Defining and clearly limiting the objective proposed and the interest of the model

The first step, like in any other simulation tool, is to set and limit the objectives to achieve. At this point it is important to ask yourself what is the information available and what can be done with this.

Step 2: Description of the processes to be modelled as well as of the interactions between them and other processes

In this second point, the processes to be modelled are described. The general processes to model and their interactions among them must be described in detail, and then the secondary processes should be introduced gradually. Knowledge of the process functioning acquires great importance, because the more information exists, the better will be the results of the model. However, the principle of parsimony must be taken into account. As has been said, the modular structure of PDP models allows adding new processes to the model with relative facility.

Step 3: Establishment of the input of the model and the parameters involved

This step is probably the most extensive and complex and requires, hence, more effort. Complex models need a large amount of data and information (inputs), which in many cases is not centralized. Therefore, it is necessary to perform an extensive previous data and information research. Moreover working together with experts on the subject to be treated is essential for successful modelling. The output of the modelling depends on the quality of the data introduced into the model. In conclusion, it can be said that the availability of data and its quality, is the main limiting factor when it comes to modelling complex problems.

Step 4: Designing a model scheme that describes the sequencing and parallelization of the processes

Although the rules and PDP modules do not require sequencing, unlike multi-agent models, the models are graphically represented as a sequence of modules. Regarding the design of the model schema it is interesting to show the parallel processes and the interactions that occur among them.

Step 5: Designing the model

At this stage the model is designed with PDP systems, once all necessary information for the model has been compiled and is available. The criterion for establishing the components of the PDP depends on the strategy adopted by the designer, however, Colomer et al. (Colomer et al., 2013) give a series of recommendations to facilitate the modelling with this type of model.

Number of environments

The first step is to define the number of necessary environments. In the case that the study area includes distinguishable physical areas with different environmental conditions, it is preferably to use a different environment for each area. In the opposite case, in which the entire study area has similar environmental characteristics, it is advisable to use a single environment.

Membrane structure

The second step in the design of the model is to establish the cell membrane structure. It is advisable to start with a system with only two membranes, the skin membrane and one inner membrane, and to introduce new membranes to the degree the complexity of the problem increases. Regarding the introduction of new membranes is preferable to create them within the skin membrane, as daughter membranes, and not within the inner membrane, because the computational cost will be lower. In any case, the fact that a higher number of membranes require an additional computational cost has to be kept in mind. Therefore, it is important to achieve a balance that allows the appropriate modelling of a specific problem without raising excessively the computational cost.

Association of objects with the actors involved in the simulation

Once the membrane structure is defined, the objects must be associated with the actors involved in the simulation. Two types of objects can be differentiated: those associated with the individuals who make up the population to study and those associated with the processes that determine the evolution of populations. Examples for the first type of objects are animals, plants or plant communities. Examples for the second type of objects, those involved in processes, are environmental conditions or feed resources. In the initial configuration, it is recommended to place the objects associated with individuals within the skin membrane, while the objects associated with processes that are similar in all environments, as for example climatic variables, should be located in the environment. This way, the correlated variables can be created in a particular environment where their distribution to other environments starts.

Set of rules

The final step in the design of the model is to write the evolution rules. These must describe the functioning of processes to model, which were previously established. In simple cases, the synchronization is already given with the possibility to apply a rule, but in more complex cases the presence of counters, which allow the application of a certain rule at the right time, is required.

Step 6: Graphical representation of the configurations that represent the execution of a model cycle

The graphical representation of the configurations comprising a complete cycle of the model has the purpose to verify that the rules are well-defined and consistent and that the model is properly synchronized. The graphical representation is particularly useful to detect possible errors, which may have occurred in the design phase of the model, since it allows following step by step all the positions of the objects, their changes and their evolutions. Figure 4 depicts a very simple example of graphical representation of a cycle’s configurations.

Step 7: Designing the simulator

PDP systems are computational models that require the design of a simulator to be applied. A free software called MeCoSim, which was developed by the Natural Computing Group of the University of Seville, is currently available (Pérez-Hurtado, 2010). MeCoSim is a visual interface that allows the configuration of the inputs and the outputs.

One of the great advantages of this simulator is the effortlessness with which the input data can be entered into the model. So, when the purpose is to study the behaviour of the model in a particular scenario, the only necessary change is the introduction of the input value in this interface.

The MeCoSim input files are of two types: *name.xls* and *name.pli*. The first one defines the menus and submenus of the simulator, the tables where the data is entered, the values of the parameters used by the model and the outputs in form of tables and graphs. The second file type, written in ASCI code, contains the model, defining the membrane structure, the initial alphabet and the evolution rules.

The simulator must be able to reproduce the inherent randomness of real processes. In these processes the objects compete with each other and are affected by a set of rules that are executed simultaneously.

2.7. PDP models and natural ecosystems

The great potential of the PDP resides in allowing the modelling of apparently complex problems, which are difficult to treat using classic models, in a simple way (Colomer et al., 2013). This is the case of natural ecosystems, in which a large number of individuals evolve individually and interact with each other and with the ecosystem.

There is a certain analogy between the PDP systems and natural ecosystems. This similarity makes the modelling with PDP a quite intuitive process. Thus, even without great mathematical knowledge, the modelling process can be easily understood graphically.

The ecosystem can be imagined as a set of physical spaces with different characteristics, which may regard environment, landscape, climate, etc. In the regions of the ecosystem the development of the individuals follows their own biological and demographic peculiarities. These individuals develop individually and interact and compete with each other and with the environment following certain guidelines or evolution rules. It is also possible that these individuals move to other areas according to certain restrictions, for example carrying capacity or lack of resources.

This representation of the ecosystem is easily applied to PDP models. The different objects situated in spaces delimited by membranes can assimilate individuals interacting in the ecosystem. Thus, analogous to individuals, objects of P systems can be transformed into other objects, create new objects, dissolve or move through different compartments or regions delimited by membranes or between different environments using evolution rules. These rules are also easily comprehensible, because they follow the same principles as a chemical reaction where the introduction of certain reagents results in certain products. This analogy helps to represent individuals in a natural way with objects, facilitating the modelling process.

The possibility to assign subscripts to objects allows the association of additional information with an object, for example the species, provenance or age. The same, though maybe less directly, occurs with other representations of objects, for example a particular surface, a specific land use or a habitat that produce certain amounts of forage available for ungulates.

In the ecosystems, the execution of the processes is synchronized and interrelated simultaneously. This synchronization can be reflected by means of the biological cycles of the organisms that constitute the ecosystem, assuming that there is an internal clock in the system (Colomer et al., 2013).

Chapter 3. Description of the study areas

"Our Pyrenees are world-famous for the beauty of their landscapes, where the grandiosity of the landform configuration harmonises with its small mountain lakes and streamlets full of juicy green plants; the mineral diversity is very high and the vegetation responds to such variation." (Montserrat, 2008)

"[...], the Stubai Valley in Austria, belongs to the Alpine 'standard region', which is mainly characterized by a specialization in livestock farming, a relatively high percentage of part-time farmers (68%), and a strong tourist component (0.5 tourist beds per inhabitant)." (Tappeiner et al., 2008)

Chapter 3

Description of the study areas

3.1. Introduction

In this chapter, the two study areas, in which the LUCC have been modelled, are presented separately: The high Catalan Pyrenees and the Stubai Valley. For each zone, their basic features are described in general terms, including the development of the agriculture and livestock farming throughout history and the socio-economic changes that have occurred in the last years. Afterwards, the physical frame and the practiced uses of soil are briefly defined, especially with regard to agricultural and farming surfaces. Finally, the main protagonists of mountain farming, large wild and domestic herbivores, are presented commenting on their basic characteristics and describing their use of mountain pastures.

3.2. The high Catalan Pyrenees

The Pyrenees are a mountain chain of southwestern Europe that separates the Iberian Peninsula from the rest of the European continent, ranging from the Bay of Biscay on the Atlantic Ocean on the west to the *Cap de Creus* in Catalonia on the east. Their length is of 450 km and the maximum width is of 150 km in their central area (Santanach et al., 1986; Sundseth, 2009). From the morphological point of view, the Pyrenees can be differentiated in Axial Pyrenees and Pre-Pyrenees. The Axial Pyrenees reach the higher altitudes, often above 3200 m, while the mountains of the Pre-Pyrenees rarely exceed 2500 m (Garcia-Ruiz et al., 1996).

The study area consists of the Catalan counties (*comarques* in Catalan) that are situated above 1700 m, corresponding, hence, with the alpine and subalpine zones (Figure 5). The Val d'Aran is the only county situated on the northern side of the Pyrenees, benefitting from the Atlantic moisture, while the rest are located on the southern side under Mediterranean influence. The surface located above 1700 m differs considerably between counties, as these areas comprise more than 50% of the surface of some counties, as for example Alta Ribagorça, Pallars Sobirà and Val d'Aran, while in other counties less than 10% of the total surface are situated at these altitudes, e.g. the cases of Berguedà and Solsonès (See table 1).

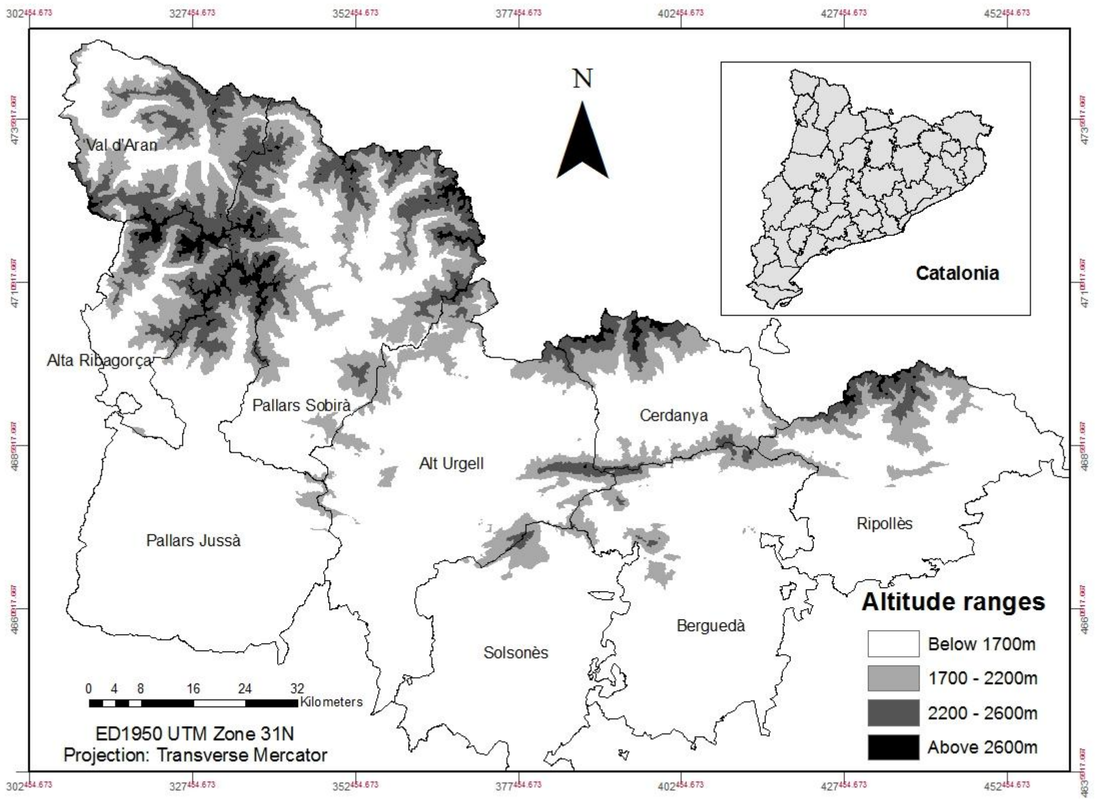


Figure 5: Study area in the nine counties (*comarques*) located in the Catalan Pyrenees. The alpine and subalpine surfaces above 1700 m are shadowed according to their altitudinal range. These zones are mostly occupied by summer grasslands, scrublands and forest (Own elaboration).

Table 1: Description of the Catalan mountain counties that comprise the study area. Own elaboration based on the data from the Statistical Institute of Catalonia (Idescat, 2013).

County	Population (2012)	Population density (2012) (inhab/km²)	Surface (km²)	Surface included into the study area (km²)	% of surface included into the study area
Alt Urgell	21,386	14.8	1,447.5	238.92	16.51
Alta Ribagorça	4,235	9.9	426.9	221.4	51.86
Berguedà	41,202	34.8	1,185.2	110.46	9.32
Cerdanya	19,047	34.8	546.7	205.9	37.66
Pallars Jussà	14,113	10.5	1,343.1	134.73	10.03
Pallars Sobirà	7,457	5.4	1,377.9	722.47	52.43
Ripollès	26,268	27.5	956.6	202.97	21.22
Solsonès	13,676	13.7	1,001.2	39.7	3.97
Val d'Aran	10,056	15.9	633.6	407.17	64.26

The presence of man in the Pyrenees dates from prehistoric times to the present day (Fillat, 2008). Farming and harvesting were the earliest forms of exploitation that have been practiced ever since in the mountains and in the valleys of the Pyrenees. In the middle ages, agriculture began due to the population increase to aim at an improved production per surface unit (Fillat, 2003b). Since then, humanity has been adapting the Pyrenean landscape to its needs: subalpine forests were deforested to increase the grazing land available for domestic animals and the montane forests were cleared to create pastures and crops fields. The Pyrenean meadows appeared more recently, wide spreading in the last 50 years, after the cereal crisis, and were managed in addition to the pastures by farmers to feed their animals. Nowadays, the montane forests still prevail in shaded areas, where the cereal could hardly grow. Moreover, large parts of beech and pine forests cover surfaces with a moderate slope, which were not used for agriculture or for rangeland expansions (Fillat, 2003b). The semi-natural meadows and pastures have formed for centuries the basis of the traditional economy, featuring, in addition, a high ecological value (Montserrat and Fillat, 1990).

Livestock farming in the Pyrenees has been linked in the course of time to *transhumance*, a technique that persists down to the present day: It consists in imitating the seasonal movements of large wild herbivores, grazing the herds in summer in the mountains and in winter in the lowlands (Lopez-i-Gelats et al., 2011; Montserrat and Fillat, 1990). In this way, the available resources are used cyclically. Livestock herds graze alpine pastures in summer and move, once the pastoral offer has been consumed, towards the hay meadows at the valley bottoms, where they spend the winter months until starting a new cycle in spring. Currently, transhumance is best maintained regarding sheep, acquiring even in this case a rather anecdotic character. Cattle herds are, if anything, subject to *transtermitance* or short-transhumance, meaning that the wintering areas are located in the Pre-Pyrenees (Montserrat and Villar, 2007).

During the second half of the 20th century, the Pyrenees have suffered profound demographic changes regarding social organization and land use, which were caused by the introduction of the capitalist system (Garcia-Ruiz et al., 1996; Lasanta and Vicente-Serrano, 2007; Lasanta-Martínez et al., 2005). The crisis of the traditional Pyrenean societies had as a main consequence the depopulation of mountain areas: a large part of the population emigrated to regional or provincial capitals and other cities, where the economic prospects were better. Especially during the 1950s and 1960s some villages were completely depopulated (Guirado and Tulla, 2010). This population decline has led to very low densities in all Pyrenean counties, as can be seen in table 1. The depopulation decelerated, temporarily with the construction of hydroelectric energy production infrastructures and, more long-lastingly, with the rise of winter tourism in certain areas (Barrachina and Tulla, 2010). The produced socio-economic changes have had as a consequence the abandonment of a large number of livestock farms (Garcia-Martinez et al., 2009; García-Ruiz and Lana-Renault, 2011). However, in general, the total animal number did not reduce, as the remaining farms increased their size, that is to say, the number of animals per farm increased. This process was accompanied by a change of the animal type: The sheep, which had been the main type of livestock, entered into a phase of regression, which is still continuing, being progressively replaced by cattle. The reasons for this change can be found in the easier management of cattle during the summer grazing, demanding less human labour, and a better adaptation to indoor production systems (Barrachina and Tulla, 2010; Bernués et al., 2011; Garcia-Ruiz et al., 1996; Komac et al., 2013; Lasanta-Martínez et al., 2005). The different features in the management of sheep and cattle causes major land-use and landscape changes. Thus, the livestock farming pressure is concentrated in the most fertile and best accessible areas and surfaces on steep slopes, which were traditionally used by sheep, are now marginalized, used very extensively, or have been entirely abandoned, so that their reforestation has started (Lasanta and Vicente-Serrano, 2007; Lasanta-Martínez et al., 2005).

Faced with the crisis of traditional activities, Pyrenean societies have had to adapt, seeking alternatives allowing the maintenance of the population and the preservation of the Pyrenees.

Unlike other mountain regions with a strong industrial sector, in many valleys of the Pyrenees tourism has been the chosen option in this situation, especially with regard to the practice of winter and mountain sports, activities related to the enjoyment of the natural environment or ecotourism. This fact implies that tourism is replacing livestock farming and agriculture (Lasanta Martínez et al., 2013; Lasanta et al., 2007) and that many of the remaining farms may have had to diversify, incorporating tourism as a component in their economies (Lopez-i-Gelats et al., 2011). The new predominance of the tourism sector can lead to a destabilisation of the other sectors, as a concentration of resources may provoke the detriment of traditional activities (Fillat et al., 2012). Although tourism, especially winter tourism, has boosted certain Pyrenean valleys, in some cases even reversing the effect of depopulation, in other areas, where the primary sector is still the most dominant, the population is aging, threatening the valleys' survival in the medium term. Neither a single focus on tourism, nor a single concentration on agriculture, ensures the conservation of the valleys. Therefore, it is necessary to develop a new model, facilitating the combination of tourism with primary activities (Lasanta et al., 2007). In the last years, several initiatives to overcome the economic dependency of the tourism sector have emerged, proposing the creation of new development models for the Pyrenees, including a boost of livestock farming and agriculture. Some examples are the Project ‘Grípia and the Shepherds School’ (Projecte Grípia i l'Escola de Pastors) or the project ‘From the field to the plate’ (Del Tros al Plat), both initiatives developed in the county Pallars Sobirà (Guirado and Tulla, 2010) which hope to promote the generational shift and the recovery and modernization of traditional activities of the mountain range.

3.2.1. Description of the physical framework

Within the description of the physical framework, the main characteristics of the Pyrenees are treated in relation to climate and geology, which are together with topography and edaphology the most important abiotic ecological factors determining the different types of pastures (Daniel Gómez, 2008). Due to the considerable extent of the study area, only the basic features defining the study area are briefly provided in this section.

Climatology

The prevailing bioclimates in the Pyrenees belong to the following type categories: cold axeric and axeromeric, also appearing xeroterics climates in the eastern zones. The cold axeric climate is characterised by the absence of any arid period throughout the year, by the lack of a real thermal summer and by the existence of a few winter months with average temperatures below 0 °C. The axeromeric climate, wetter and less cold, features neither an arid, nor a thermally glacial period, since the winter average temperatures usually keep between 0 ° and 5 °C. Finally, the xeroteric climate, a Mediterranean type, is characterised by a dry summer and a cold winter, with a maximum of 1 or 2 months with average temperatures below 0 °C (Folch et al., 1986).

In terms of absolute precipitation, the Pyrenees receive a total rainfall between 800 and 2000 mm per year, distributed over time according to the altitude (Folch et al., 1986). Additionally there are two precipitation gradients: one in North-South, from the Bay of Biscay (> 2000 mm per year) to the Ebro Valley (< 400 mm per year); and another in direction West-East in the central Pyrenees, so that there is a progressive decrease of rainfall, reaching the minimum in the vicinity of the Principality of Andorra and the county of Cerdanya. From this point the precipitation increases again due to fog and the Mediterranean rain (Badia and Fillat, 2008; Garcia-Ruiz et al., 1996).

The average temperature is 3.7 °C and the average annual precipitation is 1168 mm, according to data provided by the Catalan Meteorological Service, corresponding to 13 weather stations located within the study area. The climographs show the average precipitations and the monthly average temperature of four meteorological stations located within the study area (Figure 6). None of them shows any summer dry period. The highest precipitations are given in all cases in spring and in autumn, while the minimums are obtained in summer for the Western stations (Boí and la Bonaigua) and in winter for the Eastern stations (Cadi Nord and Núria).

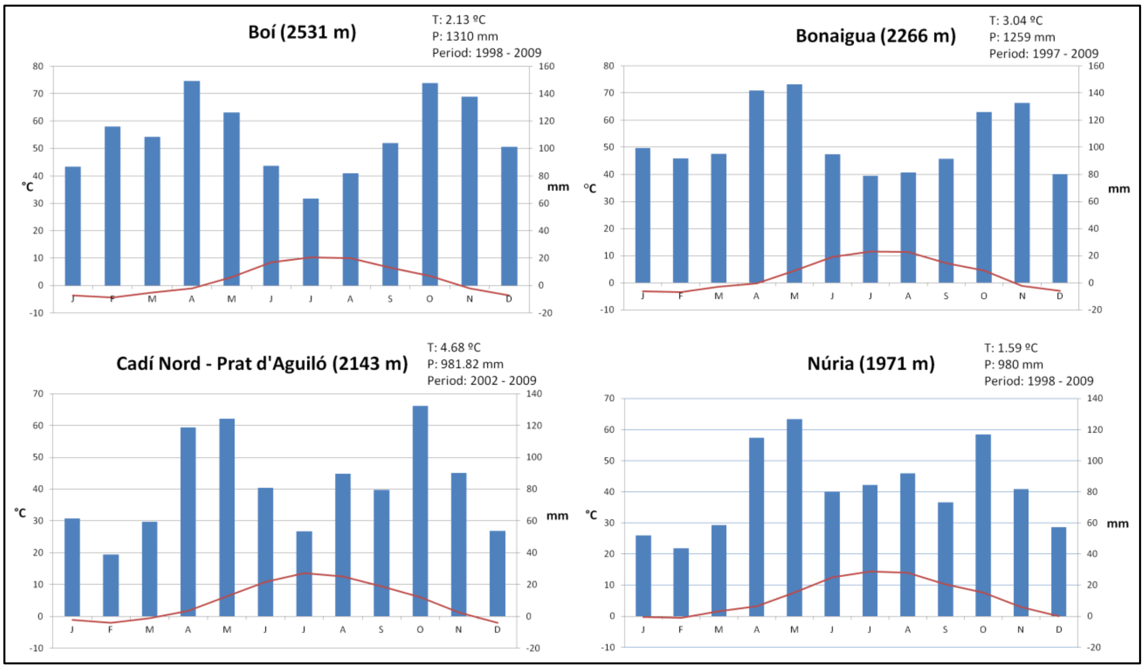


Figure 6: Climograph of four stations in the study area. The Meteorological Service of Catalonia (Meteocat) provided precipitation and temperature data. Location of meteorological stations: Boí (Alta Ribagorça); Bonaigua (Pallars Sobirà); Cadí Nord - Prat d'Aguiló (Cerdanya); Núria (Ripollès) (Own elaboration with the data provided from Meteocat (2012)).

Geology

The Pyrenees started to form due to the convergence of the Iberian and the European plates at the end of the Late Cretaceous Period, about 80 million years ago. The Alpine orogeny lasted 50 million years, coming to an end in the Miocene Epoch, after having experienced the main orogenic process in the Eocene Epoch, about 50 million years ago. The Pyrenean deformation affected, both, the Hercinian basement and the Mesozoic sedimentary covers. Climatic factors and other events, especially the glaciations, have been provoking the progressive erosion of these mountains during the Cenozoic Era, giving them their current appearance (Badia and Fillat, 2008).

The axial Pyrenees consist mainly of metamorphic and plutonic rocks, among others gneiss, granite, slate and silicates, which originated during the Palaeozoic and have been subject to distortion and erosion processes. During the Mesozoic Era and the Paleogene Period materials were deposited on either side of the axial zone, in the Pre-Pyrenees, which are mainly calcareous (sandstones, conglomerates, marls) (IGC, 2006; Santanach et al., 1986). This mountain lithology determines the quality of the pastures, being superior on calcareous substrate and inferior on granite or conglomerates. However, the richness of the calcareous soils entails karstification processes, which favour the circulation of underground water. Besides, granite and slate show less filtration, so that more streams and water accumulations facilitate the watering of the animals. Soil richness and the presence of water are two main criteria to assess the pastures' quality (Fillat, 2003a).

3.2.2. Vegetation and land uses

The vegetation of the study area shows a differentiation in altitudinal belts or zones, typical of mountain areas. Along general lines, pastures are distributed along the whole altitudinal gradient and meadows are concentrated in the low areas of the subalpine zone. The subalpine forests rarely reach their altitudinal limit and, above this tree line, already fully within the alpine zone, appear natural supraforestal pastures and zones without vegetation. The extreme climatic conditions prevailing in the subalpine and alpine zones lead to a very short growing season that lasts only a few months.

Mountain pastures

Pyrenean grazing lands can be divided into montane, subalpine and alpine pastures. Subalpine and montane pastures are secondary communities created by human action, which depend on livestock activity to maintain their structure and floristic composition. Alpine pastures and grasslands, on the contrary, are primary communities above tree line, which are ecologically permanent. Therefore, their structure and floristic composition are more influenced by abiotic changes, as for instance variations in snow cover or soil loss, than by grazing, which is usually not very important in this altitudinal belt, limited in many cases to wild ungulates (Daniel Gómez, 2008).

In the subalpine zone, formerly dominated by forests of mountain pine (*Pinus mugo sp. uncinata*), mesophile grassland of *Mesobromion erecti* and *Nardion strictae* are dominant. These two types of grasslands are the fundamental basis for the feeding of domestic ungulates and their dynamics are strongly influenced by the applied stocking rate. When the grazing pressure of livestock increases, nitrophilous communities, such as for example Polygonion avicularis and Rumicion alpini, which often develop around salt points and rest places, replace these grasslands. In the opposite case, when these surfaces are abandoned, they are rapidly colonised by grasslands of *Brachypodion pinnatum*, later by bushes of juniper (*Juniperus communis*) and, finally, by mountain pine in the last stages of the succession (Cernusca et al., 1996).

The high alpine and the upper subalpine pastures are categorized in the following classes: *Juncetea trifidi,* developing on siliceous and oligotrophics soils, and *Elyno-Seslerietea,* on calcareous and eutrophics soils. The first class includes pastures of *Festuca eskia,* characteristic of subalpine and of sunny zones at the alpine belt (*Al. Festukion eskiae*), and pastures of *Festuco airoidis*, climax grasslands of the alpine zone without snow accumulation (*Al. Festucion airoidis*). The calcareous grasslands consist of, on the one hand, pastures of *Al. Elynion myosuroidis*, which develop on the windy ridges of the alpine belt and on soils rich in bases;

and, on the other hand, mesophile pastures of the Al. *Primulion intricatae* and xeromesophiles of the Al. *Festucion scopariae* (= *Festucion gautieri*).

Mountain meadows

Meadows were the answer to a general European low grain yield in the mid-20th century, as the production and market conditions were no longer favourable (Fillat, 2003a). There are three different types of meadows, differentiated according to the altitudinal gradient and the intensity of use: valley bottom meadows, meadows on slopes and meadows that are recently used for grazing only (Chocarro and Reiné, 2008; Fillat, 2003b). The accessibility of the parcels and their distance to villages or farms determine widely their management.

Only the last two typologies appear in the study area: meadows on slopes and grazed meadows. The meadows on slopes, corresponding with *Polygono-trisetion*, occupy slopes with shallow soils and with surface runoff (Chocarro and Reiné, 2008; Fillat, 2003a). They are usually fertilized with manure or slurry, but not as intensively as meadows at the valley bottom, because of the difficulty to introduce machinery to sloped parcels. They are usually cut once per year between late June and mid-July. The meadows situated in the higher and inaccessible parts of the steeper slopes were formerly cut by hand, but are now usually used as grazing land only. These surfaces have a great importance to livestock, as they are used progressively in late spring, before the animals access the high mountain pastures, and in autumn, when the animals return from the summer zones. They can reach an altitude of up to 1800 m in sunny sides, in areas occupied by erstwhile *panars,* fields that had been used for the cultivation of cereal (Chocarro and Reiné, 2008).

Forest vegetation: forest and scrubs of the subalpine belt

Regarding woody vegetation, above 1700 m exists the coniferous forest of boreal trend, which belongs to the class *Vaccionio-Piceetea*. In the Pyrenees, the mountain pine (*Pinus mugo sp. uncinata*) forms dense subalpine forests and is the main species present at the upper limit of the forest, just below the tree line. Being a tree with edaphic indifference, it can develop on, both, north and south-facing slopes (Améztegui et al., 2010; Ninot et al., 2007). In the lower zones of the subalpine belt, at about 2000 m, the mountain pine forms forests that can be dense and well structured, but these are becoming gradually less dense and more irregular in higher altitudes. Above the tree line, it is possible to find isolated trees. The shrub vegetation is represented by dwarf shrubs (*Juniperion nanae*, *Rhododendro-Vaccinion*), in some cases as a stage of the serial succession, which is previous to forest establishment, and, in others, as permanent communities caused by soil irregularity or other specific conditions (Ninot et al., 2007).

The subalpine forest has suffered, historically, a strong deforestation, in order to expand the surface destined for pastures for domestic animals. This process known as *alpinisation* of the subalpine zone, is clearly evident on the Atlantic side of the Pyrenees and in some valleys of the southern slopes with smooth relief (e.g. Castanesa, Cabdella), where the sub-alpine forest is very scarce or totally absent. With the abandonment of the traditional activities started processes of natural regeneration, so that the subalpine forest is recovering in the lower parts of the subalpine zones (Ninot et al., 2007).

3.2.3. Livestock

The great diversity and the high energy contained in the vegetation make alpine and subalpine pastures an excellent forage source for herbivores. Nevertheless, this herbaceous biomass is only available seasonally. Wild ungulates show, therefore, altitudinal migrations, grazing only in summer in the higher altitudes, a behaviour that is imitated in human livestock management (García-González et al., 1990; Montserrat and Fillat, 1990).

Breeds of autochthonous livestock

Over the years, the mountain inhabitants selected breeds according to their adaptation to the conditions in the high mountains and regarding the purpose or the work they had to fulfil. In the following, the native breeds of domestic animals that graze the summer rangelands of the Pyrenees are presented, highlighting their main features. The provided animal censuses correspond to the genealogical book of each race on 31 December 2012 in Catalonia. All races commented are classified as in danger of extinction in the Official Catalogue of the Livestock Breeds of Spain (MAGRAMA, 2012).

In the case of bovine, the race par excellence in the Catalan Pyrenees is the Pyrenean brown breed. This breed comes from the Catalan cattle located in the Pyrenees crossed with brown cattle, which were imported from Switzerland in the late 19th and early 20th century. This breed is perfectly adapted to its environment, with the ability to graze in the high rangelands accompanied by calves. The Catalan Department of Agriculture, Livestock, Fisheries, Food and Natural Environment (DARPAMN, 2013a) estimated the breed's census in 2012 as 30,000 cows older than 2 years, out of which 11,984 were registered in the genealogical book (MAGRAMA, 2012).

Regarding the sheep, there are mainly three breeds: xisqueta, ripollesa and aranesa. The xisqueta is distributed mainly in the counties of Pallars Jussà, Pallars Sobirà and Alta Ribagorça, both in Pyrenees and Pre-Pyrenees. It is a highland rustic breed, resistant and very active, with a good reproductive fitness. The census in the Catalan Pyrenees recorded 19,518 animals. The ripollesa sheep breed is distributed in the North-East of Catalonia, mainly in the counties of Cerdanya, Berguedà, and Ripollès. Its census is 36,905 heads. Finally, the aranese breed sheep is located in the Val d'Aran, being a very rustic breed adapted to the topography of the terrain and humid and cold weather, with long snowfall periods. The strong regression experienced by the livestock farming has left this species alarmingly close to disappearance, with a census of only 3,673 animals. The most characteristic horse breed is the Catalan Pyrenean horse, multi-ethnic in origin and principally used for meat production. It is characterised by a good adaptation to the territory and by extensive breeding without stabling in winter. Its census amounted to a total of 8,410 animals. Finally, regarding goats, it is necessary to highlight the Pyrenean breed of double aptitude milk-meat, which is distributed along the whole mountain range. Previously, the Catalan goat had a certain importance but was almost extinct by the year 2005. Although a recovery process has been started, the numbers are still alarmingly low (DARPAMN, 2013a; Jordana, 2013; MAGRAMA, 2013).

Evolution of livestock censuses

To characterize the evolution of domestic ungulates in the study area, the livestock censuses are presented for the time span from 1982 to 2009 (Idescat, 2013). These censuses refer only to the animals that really graze in the mountain grasslands during the summer months, ignoring other animals, such as for example dairy cattle (see Figure 7).

When studying the evolution of domestic ungulates, first of all, a significant increase of cattle heads, which have almost doubled their number during the period 1982-2009, is observed. Secondly, ovine heads increased very significantly in the time span 1982-1986, but a constant sheep reduction is recorded since 1986. These trends clearly exemplify, how cattle generally replace sheep, all along the mountain chain. Regarding the rest of livestock, goats and horses, an ascending trend is observed in both species (Figure 7).

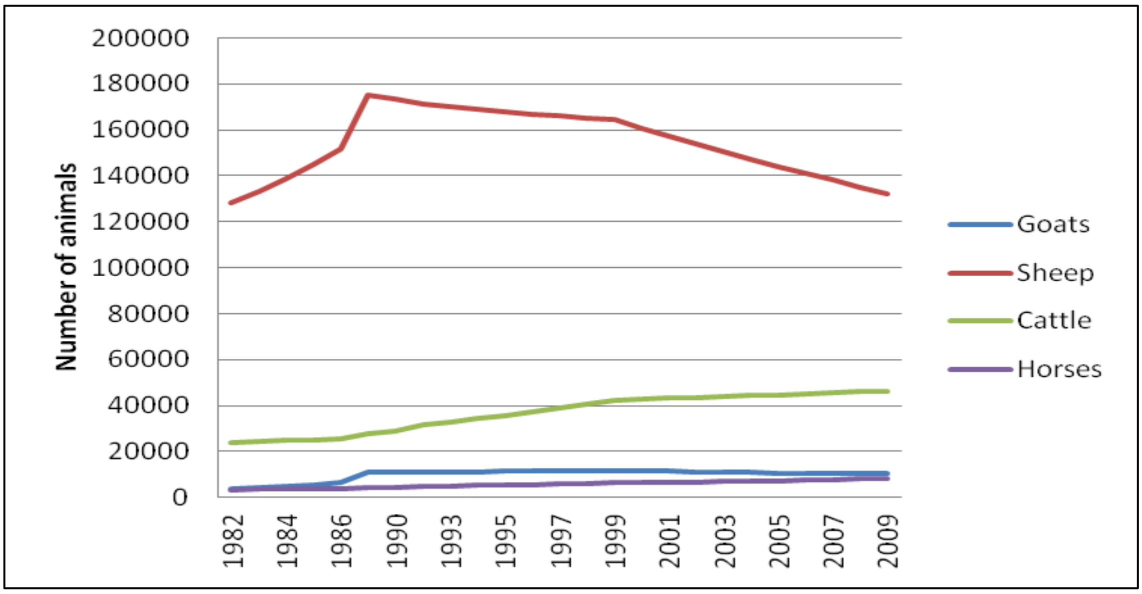


Figure 7: Evolution of livestock censuses in the study area (1982-2009). Own elaboration based on data from the Statistical Institute of Catalonia (Idescat, 2013).

Use of mountain pastures

The availability of grass determines the mobility of herds. Livestock is driven up to to mountain pastures in mid or late June and descends in mid or late October. Exact dates differ for each valley, but the summer grazing period lasts generally about 120 days. When only the study area is taken into account, i.e. the surfaces above 1700 m, this period is reduced to about 100 days (García-González, 2008; García-González et al., 1990) (Figure 8).

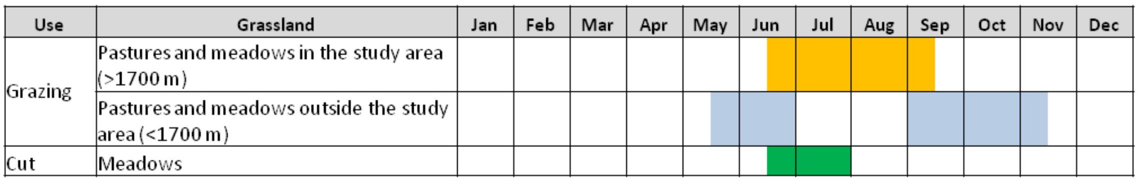


Figure 8: Land-use and livestock farming calendar in the Pyrenees.

The use of mountain pastures is different for each animal type. The ungulates are stratified in altitude depending on their body weight: the valley bottom is suitable for heavier animals, such as cows, while the steeper slopes and higher areas are only accessible to sheep . The gradual growth of vegetation in altitude requires the entry of cattle and horses little earlier than sheep. Once the animals have accessed to mountain pastures, their itineraries between different altitudinal ranges harmonize with the development of the pasture phenology, in order to use the maximum of grass production during the longest possible period of time (García-González, 2008; García-González et al., 1990). Another aspect to consider is that horses and cattle graze freely, while the movements of sheep and goat herds are largely determined by the shepherds (Lopez-i-Gelats et al., 2011). On the one hand, cattle graze preferably surfaces with gentle slopes, where dense grasses like *Bromion erecti* and *Nardion strictae* growth with relatively high productions. On the other hand, the herds of sheep graze also in communities of *Nardion strictae*, but access, moreover, the extensive pastures of *Primulion intricatae*, which are characterized by more moderate productions, but higher nutritional values. Despite their altitudinal stratification, sheep normally graze a part of the grasslands assigned to cattle, after these pastures have been grazed by cows and horses (Fillat, 2003a; García-González, 2008; García-González et al., 1990). The behaviour of the goats is in many cases similar to the sheep, as they graze together, although their feed preferences are different due to their digestive system being more adapted to the consumption of concentrates or to browse (Hofmann, 1989).

3.2.4. Wild ungulates

Wild ungulates present in the Pyrenees are the chamois (*Rupicapra rupicapra*), the red deer (*Cervus elaphus*), the roe deer (*Capreolus capreolus*), the fallow deer (*Dama dama*) and the mouflon (*Ovis musimon*). The chamois and roe deer are widespread along the mountain range and the red deer is important in certain regions, while the fallow deer and the mouflon are introduced species and have only a minor importance. The abandonment of agricultural practices has favoured the expansion of wild animals during the past few decades, colonising areas in which they had disappeared in the past (Herrero et al., 2008; Vaccaro and Beltran, 2009).

The chamois is the most emblematic ungulate in the Pyrenees. Its diet varies throughout the year, according to the availability of resources. The chamois consume preferably graminoids and woody plant on winter and herbaceous dicots on summer (Aldezabal and García-González, 2004). The chamois spent the winter in lower regions and start to climb the mountains as soon as the snow starts to melt in spring, reaching the highest peaks and ridges above the pastures used by livestock. In autumn, with the first snowfalls, the chamois return to the forest zones (Aldezabal and García-González, 2004; García-González, 2008; García-González et al., 1990). Although the chamois can share territory with livestock, especially with sheep, their different trophic habits reduce their competition for resources (Aldezabal and García-González, 2004). This species is included in the annex 2 of the Habitats Directive (92/43/EEC), meaning that the Chamois is a species of Community interest, whose conservation requires the designation of special areas of conservation. In the years 2001 and 2002, an elevate mortality rate was observed in the chamois population at the Alt Pallars National Hunting Reserve (counties of Pallars Sobirà, Alta Ribagorça and Alt Urgell), caused by the emergence of a new virus of the *Pestivirus* genus. The disease has spread to the rest of the mountain range during the last few years, reducing the Pyrenean populations (Marco et al., 2011, 2004).

Regarding forage preferences of the rest of wild ungulates, these show differences in function of their digestive system. The diet of the red deer is, similarly to the chamois, based on grazing and browsing depending on the season, so that during the summer months the woody vegetation represents only a 25% of the total alimentation. However, the red deer do not reach the same high altitudes as the chamois (Garin et al., 2001). The roe deer is a species closely linked to forest environments, being bushes the dominant part of its diet throughout the year (Virgós and Tellería, 1998). Finally, the mouflon and the fallow deer can be considered, according to Hofmann, as consumers of herbaceous species, associated with grassland habitats (1989).

3.3. The Stubai Valley

The Stubai Valley, *Stubaital*, is an Alpine Valley in Tyrol, Austria. It is located 15 km southwest of the city of Innsbruck, between the Oetz Valley and the Wipp Valley. The southern part of the valley is limited by the Italian province of *Südtirol/Alto Adige*, where the watershed acts as a natural frontier between the two States (see Figure 9).

The main valley extends 31 km from northeast to southwest and was formed during the last glacial period. Its highest peak is the *Zuckerhütl*, with an altitude of 3507 m, located at the head of the valley and still covered by the Stubai Glacier. From this glacier emanates the Ruetz River, which crosses the valley in northeast direction until merging with the Sill River outside the boundaries of the Valley (Benter and Wäldchen, 2003).

Thanks to being located near the city of Innsbruck and near one of the biggest communication routes in the Alps, the Brenner motorway, which connects Austria with Italy through the Brenner Pass, the valley is very well connected. The so-called *Stubaitalbahn* connects the valley, furthermore, since 1904 via railway with Innsbruck.

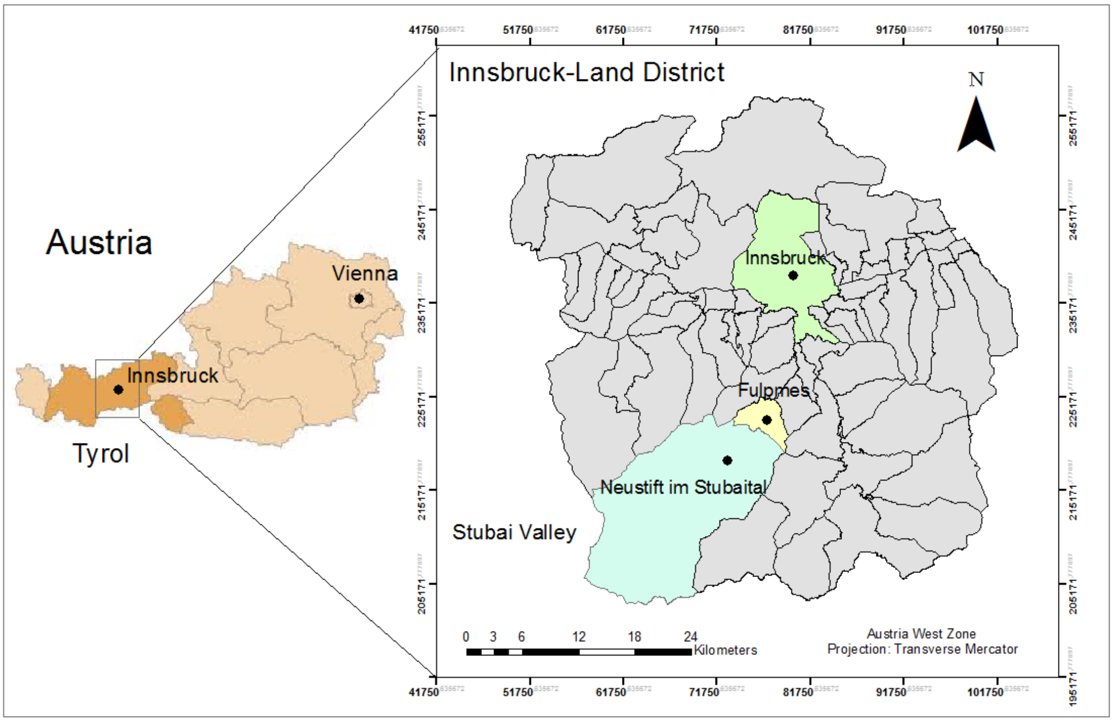


Figure 9: The study area, Stubai Valley, located in the southwest of the city of Innsbruck, in the *Innsbruck-Land* District, Tyrol, Austria.

The economic structure of the Stubai Valley has been classified by Tappeiner et al. (2008) as a *standard region* in the Alps, characterized by a specialization in livestock farming, a relative high percentage of part-time farmers, representing 68% of the total, and a strong tourist component, with an average of 0.5 tourist beds per inhabitant. Between the years 1865 and 2003, over 90% of the agricultural usable area (AUA) has undergone land-use changes (Tappeiner et al., 2008). Currently, 10% of its total surface is occupied by agricultural areas and 34% by forest (Schirpke et al., 2013b).

3.3.1. The municipalities: *Neustift im Stubaital* and *Fulpmes*

The valley is administratively divided into 5 municipalities: *Schönberg im Stubaital, Mieders, Telfes, Fulpmes* and *Neustift im Stubaital (i.S.)*, which belong to *Innsbruck-Land* District (*Bezirk Innsbruck Land*). Among these municipalities, *Fulpmes* and *Neustift i.S.* comprise the study area, corresponding to the highest part of the Stubai Valley (Figure 9).

With an area of 248.99 km^2 *Neustift im Stubaital* is one of the biggest municipalities in Austria. Due to this large surface area it is also one of the most diverse municipalities, mainly because of altitudinal variations, ranging from 1000 metres at the valley bottom to 3507 metres at the summit of the Zückerhütl. The municipality attracts tourists, both, in summer and winter, with more than 1.2 million overnight stays annually (Tasser et al., 2012a). Thanks to the tourism boom and to the proximity to the city of Innsbruck, the population has increased from 1,241 inhabitants in the year 1869 to 4,580 in 2012 (Statistik Austria, 2013). The role of agriculture and livestock farming has been declining, at the same time other sectors have increased.

Fulpmes is located at an altitude of 937 metres and covers an area of 16.77 km^2, being hence much smaller than the previous municipality. *Fulpmes* is a special case within the valley regarding its economic structure: in parallel to the tourism sector, an industrial sector has developed specialized in iron production, especially in the manufacture of tools. This municipality is also one of the main tourist centres in the valley with 350,000 annual overnight stays (Tasser et al., 2012a). The population of *Fulpmes* has also been growing continuously: quadrupling from 1,028 inhabitants in 1869 to 4,202 in 2012 (Statistik Austria, 2013). The municipality of *Fulpmes* includes also the village of Medraz. Like in the case of *Neustift*, the agricultural sector has been losing importance in recent years.

3.3.2. Description of the physical framework

The description of the physical framework of the Stubai Valley includes the characterization of the climate, the geology and the edaphology, features that determine, together with the land use and the topography, the type of vegetation developing in the study area.

Climatology

The climate in the Stubai Valley is humid continental with alpine influences, characterized by abundant precipitation throughout the year and by low temperatures in winter and mild in summer (Hörtnagl et al., 2011). The temperature and precipitation vary along the altitudinal gradient: the average annual air temperature and precipitation are 6.3 °C and 850 mm at valley sites and about 3.0 °C and 1100 mm at the tree line, near 1900 m. (Tappeiner et al., 2008). To characterize the climate of the Stubai Valley the climograph of the village of *Neustift i.S.* is provided (Figure 10).

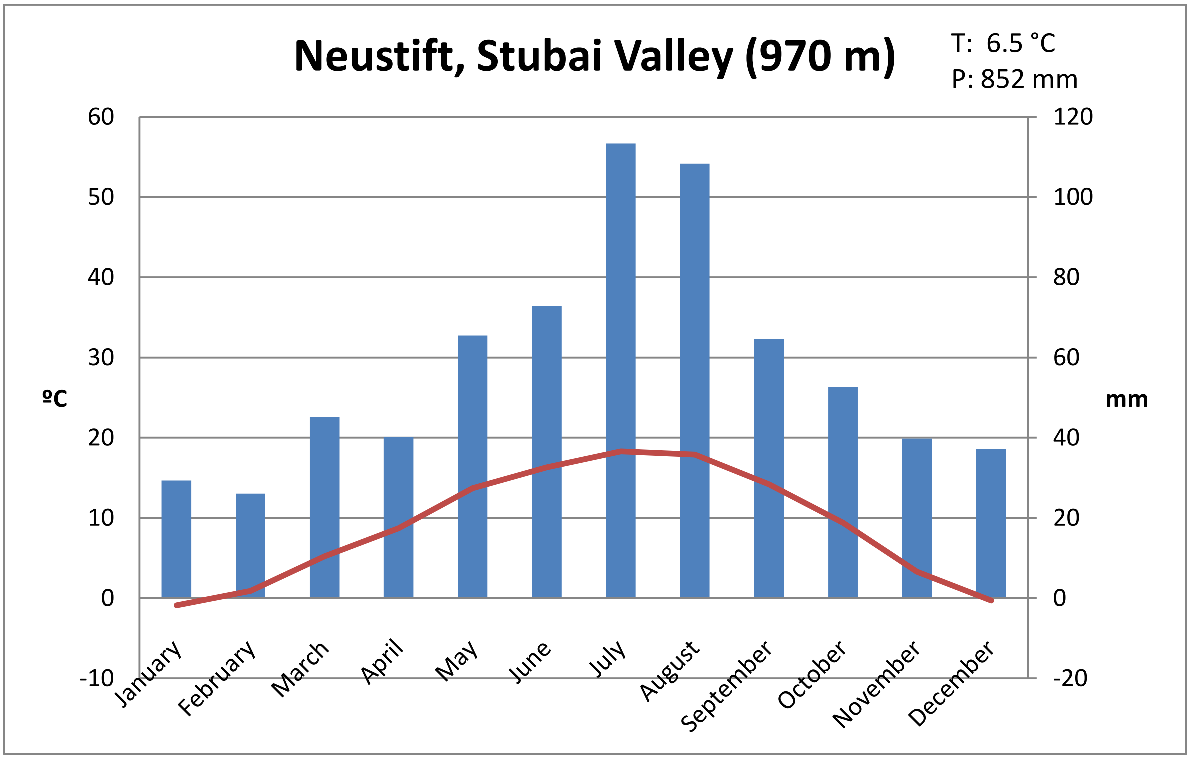


Figure 10: Climograph of Neustift im Stubaital. (From Hörtnagl et al. (2011)).

Most of the precipitation occurs during the months of June, July and August, as strong storms of short duration, often accompanied by strong wind from the north and from the west. In the months from December to March the precipitations are more scarce and 50% fall in the form of snow (Munk, 2003).

The hottest month of the year is July, while in the months of December and January the average temperatures are below 0 °C. In the Stubai Valley, an average of 150-175 days feature frost, forming a strong contrast to the 20-30 days with temperatures above 25 °C (Benter and Wäldchen, 2003).

Along with precipitation and temperature, another important factor that strongly determines the climate of the Stubai Valley is the wind. The dominant wind comes from the south, because the Valley is protected by mountain chains in the north, the east and the west. The *foehn*, a warm and dry wind that periodically descends the leeward slopes, reaches the highest wind intensities with values of 5 and 6 on the Beaufort wind force scale (Benter and Wäldchen, 2003).

Geology and edaphology

The Stubai Valley forms part of the Stubai Alps, in the Central Eastern Alps. Geologically it is included in the Austroalpine tectonic superunit, between the *Hohe Tauern* window and the *Engading* window (Froitzheim, 2013). Within the study area, the tectonic superunit is subdivided into two nappes, i.e. large bodies or sheet of rocks: the *Ötztal* Nappe, and the *Brenner* Mesozoic. The *Ötztal* Nappe is the most dominant surface nappe, while the *Brenner* Mesozoic, located above the first one, is visible only in a few specific areas: in the *Kalkkögel*, which forms the northern boundary of the Valley, and in the mountains of *Serles* between the Stubai Valley and the Wipp Valley (Munk, 2003; Ringler, 2009).

On the one hand, the Ötztal Nappe is composed mostly of silicate rocks. These rocks include mica, schist, phyllite gneiss and gneiss of sedimentary origin, which is the dominant rock. On the other hand, the Brenner Mesozoic consists of carbonate minerals, the Triassic dolomites. In the transition areas, a mixture of silicates and carbonate rocks appears, which are evident by the large number of existing rock outcrops (Munk, 2003).

With regard to soil science, calcareous areas are dominated mostly by rendzina. These soils have a different organic horizon depending on the land use: mullhumus is found in areas with pastoral use, while in other zones moderhumus appears. Moreover, podzols are the most common soils in siliceous zones. In abandoned areas, cambisols are developed, also known as brown earth, which with the coniferous forest recovery is transformed into podzols. In meadows, cambisols exist, too, as the conditions for developing podzols are not giving. Finally, the valley bottom, which is regularly flooded by the *Ruetz*, has a humus layer, known as anmoore, and soils of alluvial origin (Munk, 2003).

3.3.3. Vegetation and land uses

Along general lines, the distribution of the vegetation on the landscape can be defined as a mosaic of forest surfaces, grasslands and pastures. The vegetation can be grouped into 6 classes according to their land use: forest, intensively used grasslands, moderately intensive used grasslands, extensively used grasslands, abandoned grasslands and agriculturally non-usable area. Their distribution in the study area can be seen in figure 11.

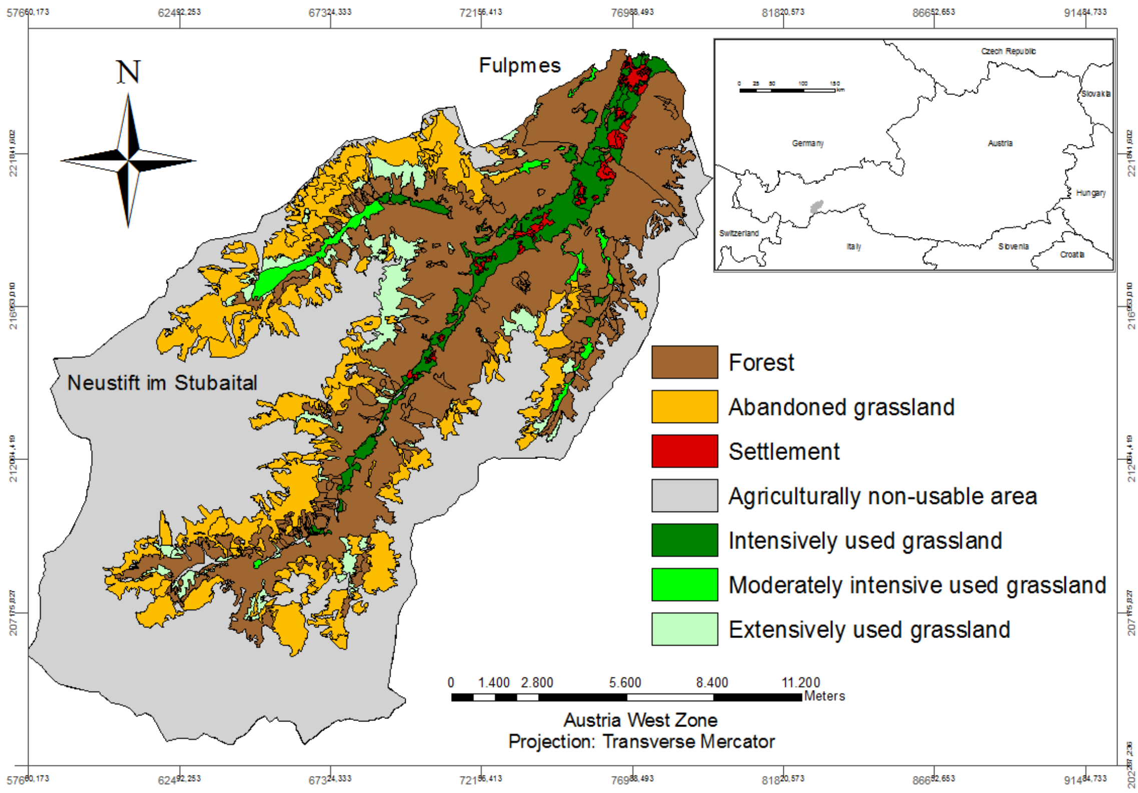


Figure 11: Land uses in the Stubai Valley in the year 2003 (Adapted from Tappeiner et al. 2008).

The forest is dominated by Norway spruce (*Picea abies*) in montane zones, between 1000 and 1600 m, with forest stands of European larch (*Larix decidua*). The forest of Eurasian stone pine

(*Pinus cembra*), European larch and mountain pine (*Pinus mugo sp. mugo*) prevails in the subalpine zone, between 1900 and 2300 m, at tree line. These tree species form the ecotone between forest and supraforestal rangelands. Deciduous species, on the contrary, do not have a significant importance in the valley, although forests of willows (*Salix sp*.), green alder (*Alnus viridis*) and European mountain ash (*Sorbus aucuparia*) are quite common (Siegl and Schermer, 2012; Tappeiner et al., 2008).

In lower areas, intensively used meadows can be found, which are highly fertilized and cut 2-3 times a year, thanks to the high precipitations. These meadows are classified as *Trisetetum flavescentis* communities and are specialized in the production of hay to feed the animals during the winter months, but they can also be used as grazing land in autumn, when the animals have descended from the mountain pastures but have not yet returned to the farms. The mowing takes place at the beginning of June, the beginning of August and at the end of September. Meadows are fertilized once a year, towards the end of October, using primarily manure (Hörtnagl et al., 2011; Tappeiner et al., 2008).

Above the intensively used meadows, between 1200 and 1800 m, exist surfaces with moderately intensive used grasslands, also known as moderately used grasslands, located within the domain of the forest. These grasslands are grazed during the first and the last summer days, enabling their use as mountain meadows between the two grazing periods. These meadows can be classified according to their altitudinal location: the lower meadows belong to the alliance *Arrhenaterion elatoris* and the higher meadows to *Polygono-trisetion*. Due to the less favourable conditions, these surfaces are only cut once a year (Land Tirol, 2012). For example, farmers in *Kaserstattalm*, mountain grasslands located in the municipality of *Neustift im Stubaital*, mow their meadows once a year, towards the end of July and fertilize with manure in autumn (Munk, 2003).

The extensively used grasslands, lightly used grasslands, located in the subalpine zone above the moderately intensive used grasslands, are used during the summer months (July-August), once the lower pastures have been grazed. These surfaces are natural or near-natural pastures, belonging to the community *Seslerio-Caricetum* (Tappeiner et al. 2008). These grasslands can be used as hay meadows with a very low intensity, cutting the grass every two years (Munk, 2003).

Apart from used grasslands exist those that have been abandoned and in which the ecological succession has been initiated through the invasion by *Calluna vulgaris*, other shrubs and tree seedlings (Tappeiner et al., 2008).

Furthermore, areas without agricultural use are found above the managed grasslands, in the alpine and nival zones. These surfaces are characterized by very low accessibility, by a lack of vegetation or by being covered with snow most of the year, featuring, hence, natural grasslands, screes and glaciers. Although these areas are not used for human agriculture, they are grazed during the summer months by some of the wild ungulates inhabiting the valley, as for instance the Alpine ibex (*Capra ibex*) and the chamois (*Rupicapra rupicapra*).

The amount of forage produced by different land uses, grazing or mowing, depends on the developed vegetation, on the altitude above sea level and on the length of the growing period, or the time in which the plants are actively producing new biomass.

The low temperatures and precipitation in the form of snow determine the short duration of the growing season At lower altitudes, around the villages, the growing season has an average duration of 200 days, at intermediate altitudes of 152 days and at higher altitudes of only 50 days a year.

3.3.4. Livestock

As mentioned before, farming livestock has lost some of the importance that it had in the past, when it was the main economic activity along with agriculture, however, it still retains a certain prominence in the Stubai Valley.

The animals present in the Stubai Valley are adapted to mountain conditions. Therefore, they are breeds that optimally take advantage of the available resources. The most common cattle breed is the *Grauvieh* of Tyrol. It is a robust and lightweight animal, very suitable for extensive farming and highly efficient when used on Alpine pastures. Regarding sheep, the most representative breed in Tyrol is the *Steinschaf*, extremely adapted to move on steep slopes. As for the goats, outstanding among the mountain breeds are the *Bündner Strahlenziegen*, the *Tauernschecken* or the *Toggenburger*. Last but not least, the Haflinger is a small and robust horse breed, the Alpine horse par excellence in Tyrol (Ringler, 2009).

When the livestock population trend is analysed for recent years (Tasser et al., 2013), a constant decrease in cattle number, the most important livestock type in Tyrol, is observed in both municipalities since the mid-20th century, when its historical maximum had been reached. However, compared with the year 1869, the total number of cows in Tyrol is still higher, especially regarding dairy cattle (Tasser et al., 2012b). With respect to sheep, the opposite situation is given. After reaching a minimum, the census has been multiplying since the second half of the 20th century until reaching a historical high in the year 2000, when a new animal reduction has been initiated, which is continuing at present. The goats have undergone a similar development as the sheep, reducing their number in the middle of the last century and recovering slightly towards the end of the century. Unlike other regions, Tyrol has witnessed in the 20th century a rise of sheep and goat herds, so that the current number of sheep is more important than in the year 1869 (Tasser et al., 2012b). A possible explanations for this trend may be the farming extensification, since sheep and goats require a more extensive dedication in time and work than cows, or the increased demand for goat milk products (Tasser et al., 2013). As to the horses, their number decreased from the early 1970s until recovering slightly towards the end of the century, remaining stable over the last 150 years. During this period, occurred a change regarding the purpose of keeping the animals, as the horses intended for agricultural work have been reduced and their recreational use have increased (Tasser et al., 2012b). Despite all the changes occurred in the study area, the total livestock units (LU) of the whole Stubai Valley is still 20% higher than in 1869 (Tasser et al., 2012b).

Figure 12 shows the evolution of the censuses of livestock by municipality for the last 140 years.

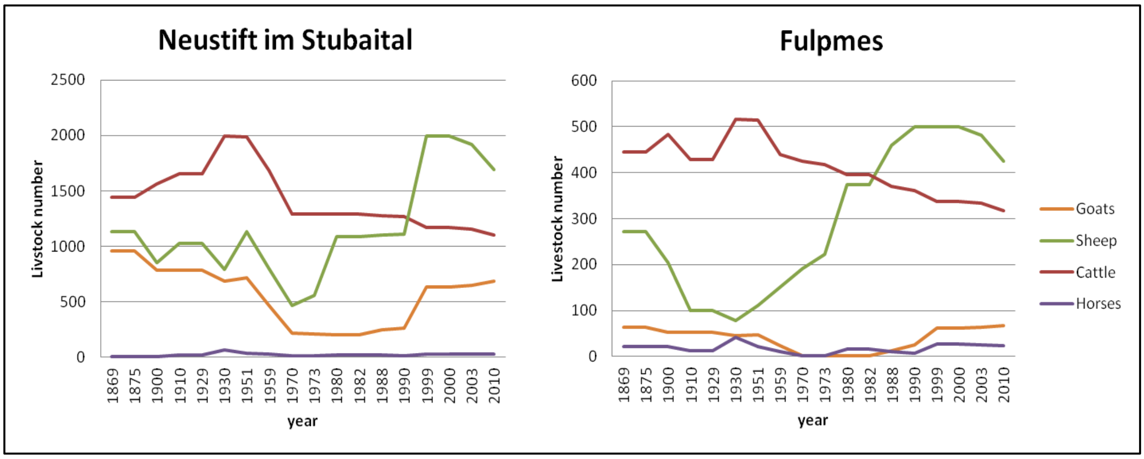


Figure 12: Evolution of the livestock number in the time span from 1869 to 2010 in the municipalities forming the study area (Source Tasser et al. (2013)).

The annual grazing cycle lasts an average of 110 days in the study area and follows, more or less, this scheme: The animals spend the winter months on the farm. Approximately at the end of May or in early June, they move up to moderately intensive used grasslands. Later, the animals are led to the extensive pastures, located above the previous ones. At the end of the summer they can graze again in the intermediate pastures before returning to the farms, towards mid or late September. At this point, and depending on the weather, the animals may graze the intensively used grasslands located near the farms at the valley bottom, extending the grazing cycle for a few days (Figure 13).

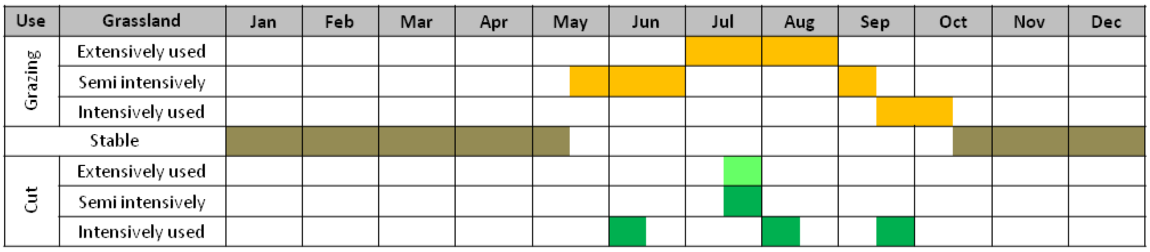


Figure 13: Livestock farming calendar of the Stubai Valley.

The use of pasture is not the same for all livestock types. Depending on the food preferences of the animals (Hofmann, 1989) and on their physical conditions, the animals graze preferentially on some surfaces to the detriment of others. In general, horses and cattle graze on flatter areas, while sheep and goats are mainly distributed on steep feeding sites (Ganskopp and Bohnert, 2009). This principle is also present in the grassland management, as the pastures are managed in accordance with the animals' characteristics and preferences. Thus, rangelands are usually divided into pastures for cows, pastures for calves, pastures for sheep, etc.

Nevertheless, not all livestock registered in the two municipalities is moved up to the high summer pastures of the valley. A significant part remains throughout the whole year in the low areas, around the farms. This situation is especially common in the case of dairy cows (Tasser et al., 2012c). Furthermore, it is important to bear in mind that the mountain rangelands are not only grazed by livestock from *Neustift* and *Fulpmes*, but can be used, additionally, by livestock coming from other nearby municipalities. In the study area, grasslands are much larger in *Neustift* than in *Fulpmes*, where grazing land is almost non-existent (see figure 11). Therefore, a large part of livestock of *Fulpmes* moves to *Neustift* during the summer months.

3.3.5. Wild ungulates

The wild ungulates present in the Stubai Valley are the chamois (*Rupicapra rupicapra*), the red deer (*Cervus elaphus*), the roe deer (*Capreolus capreolus*) and the Alpine ibex (*Capra ibex*). While the first three species are abundant and widely distributed throughout the valley, Alpine ibex populations are very small and are concentrated during the summer months at the highest peaks of the valley. Although the Alpine ibex is known as an expanding species, no reliable data has yet been obtained for the study area. Therefore, Alpine ibex have not been taken into account in this work.

The summer habitat of each of the species is different, according to their feeding type (Haesler and Senn, 2012; Hofmann, 1989). On the one hand, the roe deer behaves as a forest species and rarely enters open areas, being specialized in feeding the concentrates present in scrubs and leaves. On the other hand, the red deer and the chamois behave as grazing animals in summer. However, their spatial distribution differs, as red deer prefer low and intermediate grasslands, while chamois graze on natural pastures located at the highest altitudes, above the grasslands used by livestock (Land Tirol, 2013). In principle, wild and domestic ungulates do not compete for resources, since there is enough feed for all of them during the summer. Anyhow, especially the red deer may coincide and compete, punctually, for the resources, grazing on the same surfaces as livestock (Marchiori et al., 2012).

Tyrol in general and the study area in particular, have a great hunting tradition, resulting in a large number of hunters (over 16,000 in the whole federal state) and in a high number of hunted animals (Tiroler Landtag, 2013). Hunting is an important economic activity and the hunter associations are responsible for the maintenance of hunting species. The high density of wild ungulate populations, the high percentage of settlements and agricultural areas and the harsh weather conditions during winter, provoke that the natural feeding of wild ungulates is not guaranteed during the unfavourable season. In this context, the hunter associations provide additional feed at different points of the alpine valleys. In the specific case of Tyrol and according to its hunting law (Land Tirol, 2004), the hunter associations can provide forage to red deer and roe deer, depending on the local conditions. However, in the case of red deer supplementary feeding can only be carried out during the winter months.

Chapter 4. The PDP model to predict LUCC in mountain regions

"PDP models are at an early stage of expansion and thus it is necessary to establish a protocol for the design phase and application." (Colomer et al., 2013)

Chapter 4

The PDP model to predict LUCC in mountain regions

4.1. Introduction

In this chapter, a *Population dynamic P System (PDP)* model is presented and described to predict land-use and cover changes (LUCC) in mountain ecosystems. This chapter is mainly dedicated to the procedure proposed by Colomer et al (2013), describing certain steps for modelling with P systems.

The aim of this work is to obtain a model using a variant of P systems called Population dynamic P systems that allows predicting the future evolution and quantifying the changes that occur annually in the landscape caused by the reduction of the agricultural activity in mountain regions (LUCC).

Most of the issues treated in this chapter are common to both study areas, because they are quite similar. However, certain differences between the study areas exist, making the use of a single model impossible. These points are, therefore, commented and discussed separately, while the common features are presented at once for both study areas. The main differences occur in the step *model design*, due to the different number of administrative districts, *counties* in the case of the Pyrenees and *municipalities* in the Stubai Valley, which are represented in the model as environments. The other differences are related to the processes to be modelled.

4.2. Description of the processes to be modelled

At this point, the processes to model are described. These processes include the vital annual cycle of the wild and domestic ungulates, as well as of the high mountain plant communities, or habitats, characterized by land uses.

Thus, the processes can be separated into two groups: those related to cultural land uses and those related to ungulate grazers, both livestock and wild ungulates. On the one hand, the land-use processes are basically forage production and, in the case of pastures and meadows, their abandonment and subsequent conversion into shrubland and forest due to the reduction of farming activity. Processes related to forest fires are also included, producing the opposite effect, the evolution of woody vegetation into grasslands. On the other hand, the processes related to grazers include mortality, reproduction, wild ungulates density regulation, livestock management and grazing, as well as environment changes in the case of a lack of resources. All these modelled processes are displayed in figure 14.

4.2.1. Forage Production

Alpine and subalpine grasslands and forests produce a certain quantity of forage for grazing ungulates, varying according to land uses and the length of the growing season, i.e. the time period of new biomass production. The land-use surfaces introduced into the model are differentiated according to slope and altitudinal ranges, as their ecological characteristics vary depending on these variables. The whole area has been divided into low and high slopes, more than 30º (high or steep) and 30° or less (low), because the movement of heavier livestock is limited to moderate and gentle slopes (≤30°). The altitude has an important influence on the length of the growing season and the tree line, so that 3, respectively 4, different altitudinal ranges were defined for the Pyrenees and the Alps. The growing season is in general rather short in all altitudes of the study areas, due to the long snow cover. The standard deviation of forage production and length of growing season enable us to model the interannual variability.

Not all produced grass is available for the grazers as forage, as trampling losses have been quantified as between 30-50% (García-González and Marinas, 2008; Mosimann et al., 2012). The quantity of forage available for grazing varies when a meadow is furthermore used for the hay production, depending, hence, on the number of cuts per year and the surface used for grazing (Chocarro and Reiné, 2008; Tappeiner et al., 2008).

4.2.2. Abandonment

The agricultural and farming abandonment processes are the most difficult to quantify and, hence, to introduce into the model. The reduction of land-use intensity is represented by a reduction of grazing pressure in the model. When not all the forage produced by a grassland is grazed or mowed, an abandonment of traditional land uses is assumed. When all the grass produced by a surface unit, here one hectare, is not consumed, the unit is considered "abandoned" at a determinate ratio, as some of the zones may be margins or paths. In consequence, one of four not grazed hectares evolves into one hectare of abandoned land. The abandonment process is taken into account only for the extensive and moderately intensive meadows and pastures, because the intensively used grasslands are not affected by this process (Lasanta-Martínez et al., 2005). Moreover, this differentiation is only important in the Stubai Valley, since intensively used grasslands do not exist in the study area in the Pyrenees.

4.2.3. Landscape changes

Two opposed processes that lead to changes in the vegetation cover are introduced in this model: On the one hand, the reforestation of abandoned agricultural surfaces is very important in the high alpine areas that are the main focus of this thesis. Once a surface below the tree line has been abandoned, begins the secondary ecological succession and the surface is progressively occupied by woody vegetation. On the other hand, the recovery of pastures caused by forest fires has certain relevance at least in the Pyrenees and is therefore only considered in this study area. This process is randomly introduced into the model by means of the real incidence of natural fires in each environment, separately for tree and shrub vegetation.

It is important to remark that, in this model, the reforestation process is performed in the Pyrenees by means of two steps: firstly, abandoned land can evolve into shrublands, and secondly shrublands can evolve into forest. In the Alps, this process comprises only one step, so that the abandoned land evolves directly into forest. These differences in the reforestation processes are given due to the land-use classes considered in the covers of the study areas.

4.2.4. Livestock management

The domestic livestock is largely influenced by farmer decisions, for instance, regarding the animal number and type. Therefore, the number of domestic mountain grazers depends more on socio-economic factors than on biological processes. Modifications are possible every year, so that a wide range of future scenarios is imaginable. In consequence, the number of grazers in high mountain pastures is modified to simulate land-use changes, according to hypothetical changes in rural dynamics, as well as reforms of the Common Agriculture Policy (CAP) (e.g. Bayfield et al., 2008).

4.2.5. Reproduction and mortality

Reproduction and natural mortality of each herbivore species are modelled by means of their biological parameters. In the case of the wild ungulates these processes have more importance than in the case of the domestic grazers, because farmers largely determine these livestock dynamics. The population dynamics of wild grazers are also affected by hunting. In this work, natural mortality is separated for each species into adult mortality and mortality affecting animals younger than one year. Moreover, the percentage of hunted ungulates is differentiated into males, females and young animals.

4.2.6. Grazing and density regulation

Grazing and density regulation are two differentiated but closely related processes, so that they are described together.

Grazing processes differ for each animal type according to its characteristics, as the ungulates choose their diet based on forage preferences (Hofmann, 1989) and on the possibility to access certain slopes depending on the animal type (Ganskopp and Bohnert, 2009; García-González et al., 1990; Montserrat and Fillat, 1990; Ringler, 2009). Livestock graze high rangelands between 100 and 120 days in summer. All livestock types can graze on low slopes (≤30°), but only sheep and goats can access steeper slopes (>30°). Wild ungulates obtain most of their aliment in surfaces that are not used for agriculture, but they can also graze on the same pastures and meadows as livestock, competing for the same resources (Marchiori et al., 2012). In the case of wild animals, it is necessary not to exceed the maximum carrying capacity of the environment, in order to carry out the grazing process. When animals are unable to satisfy their nutritional and density requirements, they can access another administrative district (county or municipality), at least as long no restrictions prevent this. These animal displacements are represented in the model with a change of environment. In the Alps, all animals can move among environments, but in the Pyrenees only wild ungulates can move to adjacent environments.

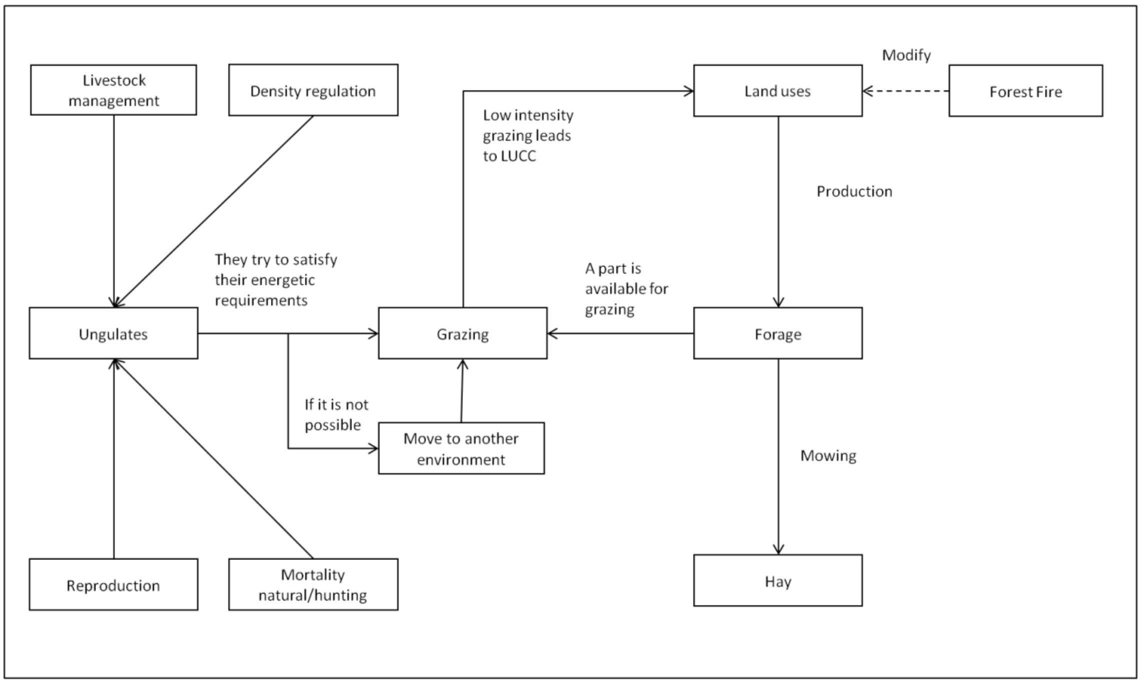


Figure 14: Modelled processes: Interactions and parallelisms. Ungulates and land uses evolve independently but interact with each other in some processes. Forest fires are only considered for the Pyrenees (dotted line).

4.3. Model inputs and involved parameters

The inputs and the parameters involved in the model are different in each study area, so in this section they are treated separately for the Catalan Pyrenees and for the Stubai Valley. In some cases the inputs and parameters introduced into the model are not directly obtained from literature, but were calculated or derived from other data. All geo-processing data are carried out by means of ArcGis 9.3 (Esri®, California, USA). All data is provided in annexes A and B.

4.3.1. Study case 1: Catalan Pyrenees

In this work, the vegetation that develops in the alpine and subalpine zones is grouped in 6 different classes: (1) alpine and subalpine pastures, (2) mountain meadows, (3) boreal coniferous forest, (4) shrub communities and (5) open spaces with little or no vegetation (CREAF, 2013). Apart from these basic land uses, an additional land-use class has been introduced, called (6) abandoned land, which includes the pastures and meadows that are no longer used for agriculture or livestock farming.

Regarding the land-use surfaces of the study are, each administrative district is separated into three altitudinal and two slope ranges, in order to model the ecosystem as correctly as possible. The land-use layers are the Land-Use Map of Catalonia (MCSC) for the years 1993 and 2009 (CREAF, 2013). The version of 1993 has derived from ortophotos with a scale of 1:25.000, having a pixel resolution of 2.5 m. For the version of 2009, the scale of the ortophotos was 1:2500 and the pixel resolution 0.25 m. The digital elevation model (DEM) was calculated from topographic layers provided by the Cartographic Institute of Catalonia (ICC, 2010). The whole surface is classified into three altitudinal ranges: a low altitudinal zone - from 1700 to 2200 m -, an intermediate zone - from 2200 to 2600 m -, and an upper zone - more than 2600 m. The first and the second range can be considered as low and high subalpine belts, while the third comprises the alpine and the nival belt (Badia and Fillat, 2008). The slope is reclassified in two slope ranges, greater than 30° and less than or equal to 30°, in order to limit the access of cattle and horses to grazing lands located on steep slopes (>30°).

The beginning of the growing season is defined by means of the thermal integral, using the temperature data provided by the Meteorological Service of Catalonia for different stations placed in the study area. The period begins, for each altitudinal range, when the sum of positive daily temperatures, accumulated since the beginning of the year, exceeds 300 °C. The end of the period is set from the consulted references (D Gómez, 2008).

The list of all the inputs and parameters introduced into the model are provided in table 2, together with the respective sources.

Table 2: Inputs and parameters introduced into the model for the Catalan Pyrenees

Symbol	Definition	Source
$g_{i,1}$	1 wild animal and 0 domestic animals	13
$g_{i,2}$	Age when adult size is reached	13
$g_{i,3}$	Age when fertility begins	13
$g_{i,4}$	Age when fertility ends	13
$g_{i,5}$	Average life expectancy in the ecosystem	13
k_1	Percentage of females present in the population	13
k_2	Fertility ratio	13
k_3	Number of descendants per fertile females that reproduce	13
m_1	Natural mortality ratio in first years, age < g_2	13
m_2	Mortality ratio in adult animals, age > g_2	13
h_1	Percentage of male adult animals hunted	13
h_2	Percentage of female adult animals hunted	13
h_3	Percentage of young animals hunted	13
f_i	Animals' energetic requirements (kg DM day^{-1})	15
pf_{ijs}	Grazing preferences of the species *i* in land use *l* and on slope *s*	4,5,7 and 17
pm_{iuv}	Possibility that the animal *i* moves from the environment *u* to *v*	Based on the environments' location and livestock management
p_{1i}	Population of the species *i* in the administrative district *k*	11
d_{ik}	Maximum carrying capacity, species *i*, environment *k*	13
$Incr_{i,k,y}$	Percentage of annual increase of the species *i*, environment *k* and year *y*	Calculated from 11
$Decr_{i,k,y}$	Percentage of annual decrease of the species *i*, environment *k* and year *y*	Calculated from 11
$G_{i,k}$	Percentage of domestic grazers in environment *k*	Calculated from 11
$S_{l,a,s,k}$	Surface (ha) of land use *l*, altitude *a* and slope *s* in environment *k*	Derived from 2 and DEM
μR_l	Average plant production (kg DM ha^{-1} y^{-1}) in land use *l*	10
σR_l	Standard deviation of plant production in land use *l*	Calculated from 10
$\mu T_{l,a}$	Average length of the growing season in land use *l* and altitudinal range *a*	Determined from climatologic data and 8
$\sigma T_{l,a}$	Standard deviation of the growing season in land use *l* and altitudinal range *a*	Determined from climatologic data and 8
ug_l	Percentage of grasslands used in land use *l*	6
mw_l	Percentage of available grass after mowing in land use *l*	1 and 14
δ_k	Summation of all the surfaces of environment *k*	Calculated from $S_{l,a,s,k}$
rp_s	Reforestation probability in altitudinal range *a*	Estimated from 12 and 16
rp_f	Shrub encroachment probability in altitudinal range *a*	Estimated from 12 and 16
fs	Hectares of burned shrubland	3
ft	Hectares of burned forest	3
NZ	Values of a normal distribution *N*(0,1)	-

Source: 1, Chocarro and Reiné (2008); 2, CREAF (2013); 3, DARPAMN (2013); 4, García-González et al. (1990); 5, García-González (2008); 6, García-González and Marinas (2008); 7, Garin et al. (2001); 8, Gómez (2008); 9, Hofmann (1989); 10, Idescat (2011); 11, Idescat (2013); 12, Lasanta-Martínez et al. (2005); 13, Margalida and Colomer (2012); 14, Montserrat and Fillat (1990); 15, Ringler (2009); 16, Roura-Pascual et al. (2005); 17, Virgós and Telleria (1998).

4.3.2. Study case 2: Stubai Valley

The vegetation in the Stubai Valley has been classified according to the cultural land uses, including (1) intensively, (2) moderately intensive and (3) extensively used grasslands; (4) abandoned land; (5) agriculturally unprofitable areas and (6) forest (Tappeiner et al., 2008).

The land-use surfaces introduced into the model were separated in different altitudinal and slope ranges according to their different ecological characteristics. Based on the vectorial cultural land-use covers of the municipalities of *Fulpmes* and *Neustift i.S.* (Tappeiner et al., 2008) and the digital elevation model (DEM) with a pixel resolution of 10 m, (tiris, Land Tirol (c)), the whole area was divided into two slopes, greater than 30° and less than or equal to 30°, and 4 altitudinal ranges: 886-1500 m, 1500-2150 m, 2150-2600 m, and 2600-3493 m. The altitude influences the length of the growing season, the plant production (Egger et al., 2003) and the natural reforestation (Tasser et al., 2007).

The probability that abandoned land is reforested was calculated by means of a double exponential function, using as explanatory variables the altitude in meters (x_1) and the time since abandonment in years (x_2) (Tappeiner et al., 2008; Tasser et al., 2007). In our case, the time since abandonment is always 1 year (Equation 3), as the probability of abandonment is applied every year.

$$p_{forest} = 1 - e^{-116.128 \cdot e^{-0.00613 x_1} \cdot x_2} \qquad \text{Equation 3}$$

This expression has not been applied in the Pyrenees, because the conditions and tree species of the Alps differ from the Pyrenees, so that the expression developed for the Alps is not applicable. In the Pyrenees, it has not been possible to obtain a similar expression.

The inputs and parameters introduced into the model, together with their respective sources, are provided in table 3.

Table 3: Inputs and parameters introduced into the model for the Stubai Valley.

Symbol	Definition	Source
$g_{i,1}$	1 wild animal and 0 domestic animals	8,15
$g_{i,2}$	Age when adult size is reached	8,15
$g_{i,3}$	Age when fertility begins	8,15
$g_{i,4}$	Age when fertility ends	8,15
$g_{i,5}$	Average life expectancy in the ecosystem	8,15
k_1	Percentage of females present in the population	8,15
k_2	Fertility ratio	8,15
k_3	Number of descendants per fertile females that reproduce	8,15
m_1	Natural mortality ratio in first years, age < g_2	8,15, calculated from 7
m_2	Mortality ratio in adult animals, age > g_2	8,15, calculated from 7
h_1	Percentage of male adult animals hunted	15, calculated from 7
h_2	Percentage of female adult animals hunted	15, calculated from 7
h_3	Percentage of young animals hunted	15, calculated from 7
f_i	Animals' energetic requirements (kg DM day^{-1})	10
pf_{ijs}	Grazing preferences of the species *i* in land use *l* and on slope *s*	3,10
pm_{iuv}	Possibility that the animal *i* moves from the environment *u* to *v*	Based on the environments' location and livestock management
p_{1i}	Population of the species *i* in the municipality of *Fulpmes*	7, 13
p_{2i}	Population of the species *i* in the municipality *Neustift im Stubaital*	7, 13
d_{ik}	Maximum carrying capacity, species *i*, environment *k*	7
$Incr_{i,k,y}$	Percentage of annual increase of the species *i*, environment *k* and year *y*	Calculated from 13
$Decr_{i,k,y}$	Percentage of annual decrease of the species *i*, environment *k* and year *y*	Calculated from 13
$G_{i,k}$	Percentage of domestic grazers in environment *k*	Calculated from 13
$S_{l,a,s,k}$	Surface (ha) of land use *l*, altitude *a* and slope *s* in environment *k*	Derived from 11 and DEM
μR_l	Average plant production (kg DM ha^{-1} day^{-1}) in land use *l*	Calculated from 1,5,6,11 and DEM
σR_l	Standard deviation of plant production in land use *l*	Calculated from 1,5,6,11 and DEM
$\mu T_{l,a}$	Average length of the growing season in land use *l* and altitudinal range *a*	Determined from DEM according to 2
$\sigma T_{l,a}$	Standard deviation of the growing season in land use *l* and altitudinal range *a*	Determined from DEM according to 2
ug_l	Percentage of grasslands used in land use *l*	1,9
mw_l	Percentage of available grass after mowing in land use *l*	4, 14
δ_k	Summation of all the surfaces of environment *k*	Calculated from $S_{l,a,s,k}$
rp_a	Reforestation probability in altitudinal range a	Calculated from 11, 12 and DEM
NZ	Values of a normal distribution $N(0,1)$	-

Source: 1, Egger et al. (2003); 2, Harlinger and Knees, (1999); 3, Hofmann (1989); 4, Jeangros and Troxler (2008); 5, Klug-Pümpel (1978); 6, Klug-Pümpel (1989); 7, Land Tirol, Department of Agricultural Hunting and Fishing (2012); 8, Margalida and Colomer (2012); 9, Mosimann et al. (2012); 10, Ringler (2009); 11, Tappeiner et al. (2008); 12, Tasser et al. (2007); 13, Tasser et al. (2013); 14, Thomet et al. (1991); 15 Tiroler Jägerverband (1999).

4.4. Designing a model scheme that describes the sequencing and parallelization of the processes

The model is organised in 2 cycles, involving 12 sequenced modules that are able to run more than one process at the same time. One cycle contains all the processes relayed to ungulates dynamics and the other to cultural land uses. They work in parallel, independently and randomly, and interact with each other in the processes of grazing and environment change. This model scheme is shown in figure 15.

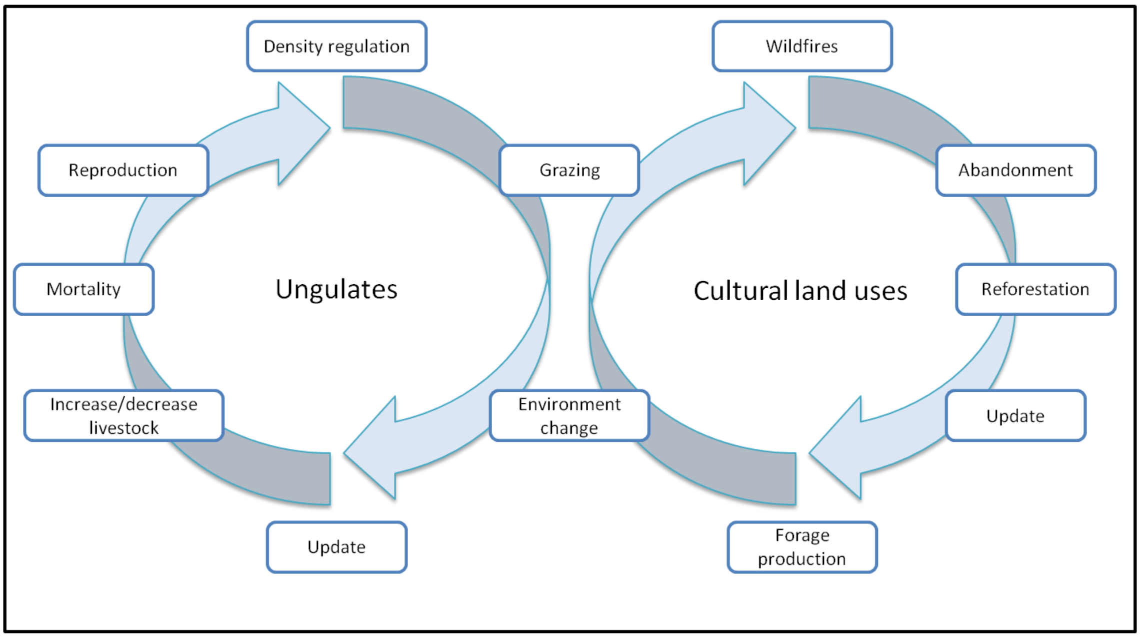


Figure 15: Sequencing of the processes to model. Each cycle represents the summer grazing period. The modules related to environment change are only applied in the case of a lack of forage. The wildfires module is only included in the model for the Pyrenees.

4.5. Designing the model

Designing the PDP model for the study of LUCC in alpine regions, involves defining the number of environments, the membrane structure, the working alphabet and the evolution rules. In the model designs exist some differences between the Pyrenees and the Alps. Therefore, a generic design of the model is presented, which includes all the possibilities in order to facilitate an easy adaptation to each case study. However, it is indicated whenever certain aspects are specific or were only considered in one of the two study cases, as for instance the number of environments or wildfire processes.

4.5.1. Number of environments

The number of environments depends on the number of physical zones present in the ecosystem. A virtual environment is added to simplify and reduce the computational cost of modelling environment changes due to a lack of resources, mainly forage available for grazers, but also space. Considering that the total number of environments representing physical zones and administrative districts is E, the label that identifies each is 101, 102, etc. until reaching $100 + E$ for the last. Furthermore, an additional environment is introduced, which is called in the following *virtual environment,* as it is not directly related to any physically existing zone. It is labelled with $100 + E + 1$.

The represented physical environments are 9 counties in the Pyrenees, and 2 municipalities in the Alps (see chapter 3). Thereby, the ecosystem placed in the Catalan Pyrenees comprises 9+1 environments (the real environments plus the virtual environment), while the ecosystem studied in the Alps includes only 2+1 environments. In the work in the Alps, the third membrane would not be necessary as only 2 environments are differentiated. However, it has been introduced to enable the introduction of further environments in the future.

4.5.2. Membrane structure

The membrane structure of each environment consists of a skin membrane (labelled 0), which contains two internal membranes (labelled 1, 3). Membrane 2 is situated within membrane 1 (Figure 16). This structure is repeated for each cell in each environment. The subscript *p* represents the entire system.

Membrane structure:

$$\mu = \left[[[[[\ \ ]_2]_1[\ \ ]_3]_0]_{101} \dots [[[\ \ ]_2]_1[\ \ ]_3]_0]_{(100+E+1)} \right]_p$$

Although each environment represents municipalities or administrative districts, no similar correspondence is given regarding the membranes, which are used to carry out the different processes. The reproduction processes are carried out in membrane 1. The mortality and the grazing modules are developed in the membranes 1 and 2. The increase or decrease of the domestic ungulates is placed in the environment, outside the skin membrane. The processes related to forage production are developed in the environment (outside the skin membrane) and in the membrane 0. Land cover changes that include abandonment and reforestation are performed in the membranes 0 and 1, while pasture recovery by wildfires occurs only in the skin membrane. Finally, with the membrane labelled as 3 the update module is carried out.

The virtual environment, labelled as $100 + E + 1$ is only used to carry out the grazing process when animals are forced to change the environment due to a lack of forage. In this case the grazing process takes place in membrane 0.

4.5.3. Initial working alphabet

The alphabet of the initial configuration is provided separately according to the membrane in which the objects are placed. In the initial configuration most of the objects, especially those that are associated with the inputs of the model, are placed inside the skin membrane. Only some objects are placed initially inside other membranes to facilitate their participation in the modelling processes. The location of all objects in the initial configuration inside the membranes is shown in figure 16.

In the skin membrane, membrane labelled as 0, applies the following initial alphabet for all environments except the virtual:

$$M_0 = \left\{ X_{ij}^{qX_{ij}}, XA_{dj}^{qXA_{dj}}, A_{las}^{qA_{las}}, a_i^{qa_i}, \varphi_{las}^{q\varphi_{las}}, S^{qS}, T^{qT} \right\}, 1 \le i \le w, w+1 \le d \le N, 1 \le j \le g_{i5}, 1 \le l \le LU, 1 \le a \le h, 1 \le s \le 2.$$

Where w is the number of wild ungulates, N is the number of animal species, LU is the number of land-use types or habitats, and h is the number of defined altitudinal ranges. Superscript q represents the multiplicities of each object.

The initial alphabet in the skin membrane of the virtual environment is as follows:

$M_0 = \{RE_0\}$.

In all the membranes labelled as 1, except for membrane 1 in the virtual environment, applies the following initial alphabet:

$M_1 = \{R\}$.

Finally, the initial alphabet for the environments, representing real physical environments, is as follows: $\{D_{i0}, \Omega_1\}, 1 \leq i \leq w$.

Each animal is associated with an object X_{ij} (wild ungulates) or X_{dj} (domestic grazers) with two subscripts. The first index represents the species (i for wild and d for domestic) and the second, j, the age range. The object A_{las} represents a unit surface (in this case 1 ha) of the cultural land use l, situated in the altitudinal range a and in the slope range s. Object φ_{las} represents 1 kg of dry matter produced in one season (kg DM year^{-1}) by the land use l in the altitude a and on the slope s available for grazing. Objects D_{i0} are counters that allow creating objects a_i, which will be used to control the maximal environmental carrying capacity for wild animals. The object Ω_y controls the year in which the reduction or increase of domestic animals must be performed. T and S represent an hectare of the surface covered by forest and shrub respectively not taking into account in the study area. Finally R and RE are counters that are used for synchronization: R in the environments related to physical zones and RE only in the virtual environment.

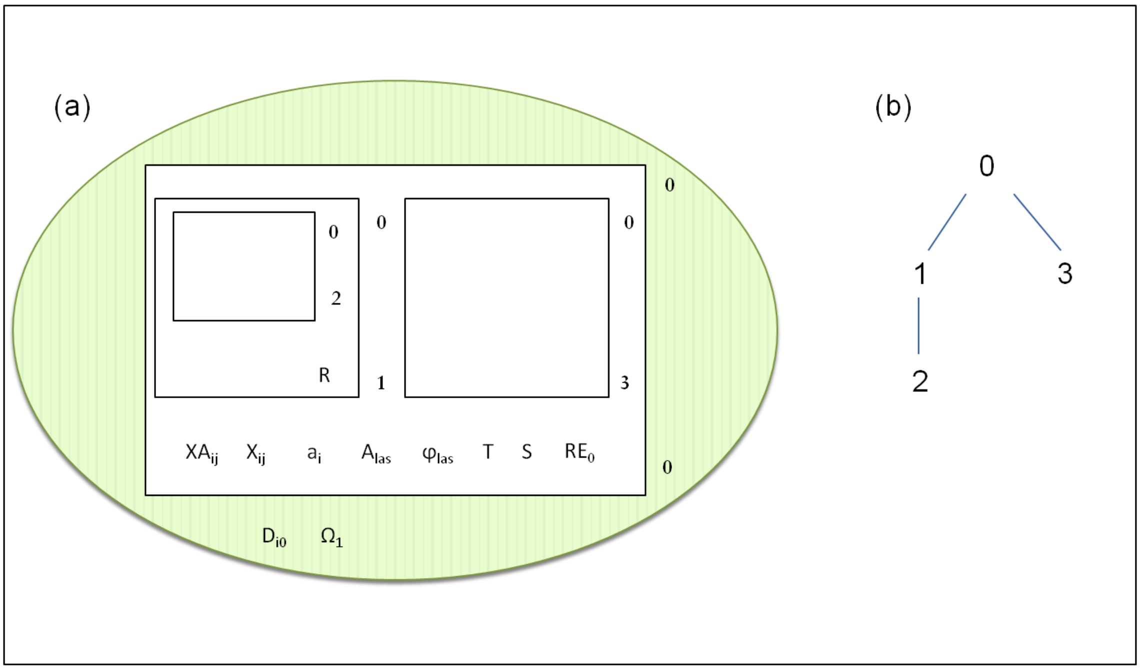


Figure 16: Representation of (a) the cell and (b) its associated tree. In the cell, the initial configuration of the model is represented. This is a generic representation, but note that the counter RE_0 appears only in the virtual environment, being the only object present in this configuration, as has been defined above.

4.5.4. Evolution rules

Following the scheme proposed in figure 15, a set of rules was defined. All of them are provided and commented below. They are differentiated into three groups depending on which objects are affected: (1) those relating to counters; (2) those regarding animals and (3) those relating to land uses. Table 4 shows the symbols used in the rules together with their definition and table 5 displays the analytical expressions introduced into the model.

Table 4: Relation of symbols used in the model rules

Symbol used in the rules	Definition
N	Number of grazers
w	Number of wild ungulates
w+1	Subscript for goats
w+2	Subscript for sheep
w+3	Subscript for cattle
w+4 = N	Subscript for horses
LU	Number of land-use types
h	Number of altitudinal ranges
E	Number of physical zones
E+1	Number of environments / Label of virtual environment
Y	Number of simulated cycles (years)

Table 5: Equations used in the rules

Description	Equation
Adult males	$p1 = 1 - \frac{k_{i,j}(1-ht_{i,2})^j}{k_{i,1}(1-ht_{i,2})^j + (1-k_{i,1})(1-ht_{i,1})^j}$
Adult females that reproduce	$p2 = k_{i,2}\frac{k_{i,1}(1-ht_{i,2})^j}{k_{i,1}(1-ht_{i,2})^j + (1-k_{i,1})(1-ht_{i,1})^j}$
Adult females that do not reproduce	$p3 = (1-k_{i,2})\frac{k_{i,1}(1-ht_{i,2})^j}{k_{i,1}(1-ht_{i,2})^j + (1-k_{i,1})(1-ht_{i,1})^j}$
Wild adult ungulates that die naturally or by hunting	$p4 = m_{i,2} + \frac{ht_{i,2}k_{i,1}\left((1-ht_{i,2})^{g_{i,2}} + (1-ht_{i,2})^{g_{i,5}}\right)}{\left((1-ht_{i,2})^{g_{i,2}} + (1-ht_{i,2})^{g_{i,5}}\right) + \left((1-ht_{i,1})^{g_{i,2}} + (1-ht_{i,1})^{g_{i,5}}\right)} + \frac{ht_{i,1}(1-k_{i,1})\left((1-ht_{i,1})^{g_{i,2}} + (1-ht_{i,2})^{g_{i,5}}\right)}{\left((1-ht_{i,2})^{g_{i,2}} + (1-ht_{i,2})^{g_{i,5}}\right) + \left((1-ht_{i,1})^{g_{i,2}} + (1-ht_{i,1})^{g_{i,5}}\right)}$
Forage production (kg DM ha^{-1} year^{-1})	$prod = ug_l mw_l (NZ_{i,j}\sigma R_l + \mu R_l)(NZ_{i,j}\sigma T_{l,a} + \mu T_{l,a})$

4.5.4.1. Counter rules

Rules with R counter

R counters are located inside the membrane 1 of all environments except the virtual environment $(E+1)$. Their role is to synchronize the processes that occur in these environments, as for example a membrane's charge changes (e.g. rules 1 and 4) or the creation of new objects at specified moments of the cycle (e.g. rules 2 and 5).

$r_1 \equiv [R]_1^0 \to [R, co]_1^+.$

An object ff is created to begin the processes related to forest fires.

$r_2 \equiv [R]_1^+ \to ff[R_0]_1^0.$

$$r_3 \equiv \left[R_i \to R_{i+1}\right]_1^0, \begin{cases} 0 \le i \le 16, \\ i <> 3, \\ i <> 11, \\ i <> 14 \\ i <> 15. \end{cases}$$

$r_4 \equiv R_3[\quad]_2^+ \to R_4[b]_2^-.$

The object R_{13} creates, apart from the object R_{14}, a new object TR, which is used in the introduction of randomness in the length of the growing season and in the grass production.

$r_5 \equiv [R_{11}]_1^0 \to TR[R_{12}]_1^0.$

$r_6 \equiv [R_{14}]_1^0 \to b[R_{15}]_1^-.$

$r_7 \equiv [R_{15}]_1^- \to [R_{16}]_1^0.$

$$r_8 \equiv \left[R_{17} \to R\right]_1^0.$$

Rules with object b

The objects b and co and their variants are created to change the charges of the membranes. These changes are required for the development of some of the processes to be modelled.

$r_9 \equiv [b]_2^- \to [\quad]_2^0.$

$r_{10} \equiv b[\quad]_3^0 \to [b]_3^-.$

$r_{11} \equiv [bE]_3^+ \to [\quad]_3^0.$

$r_{12} \equiv [b]_3^- \to [b1]_3^0.$

$r_{13} \equiv [b1]_3^0 \to [b2]_3^+.$

$r_{14} \equiv [b2]_3^+ \to [\quad]_3^0.$

Rules with co objects

$r_{15} \equiv co[\quad]_2^0 \to [co]_2^+.$

$r_{16} \equiv [co]_2^+ \to [\quad]_2^+.$

Rules with RE counters

The RE counter is placed in the membrane 0 of the virtual environment ($E+1$), in which the processes of grazing take place, whenever animals leave their original environments due to a lack of resources. The function of this object is the same as for the objects R: synchronizing the different steps of the model.

$$r_{17} \equiv \left[RE_i \rightarrow RE_{i+1}\right]_0^0, \begin{cases} 0 \leq i \leq 18, \\ i <> 13. \end{cases}$$

$$r_{18} \equiv RE_{13}[\quad]_3^0 \rightarrow RE_{14}[bE]_3^+.$$

$$r_{19} \equiv \left[RE_{19} \rightarrow RE_0\right]_0^0.$$

Rules with D counters

The counters D_i are objects that create new objects a_i and e_i, which regulate the maximal carrying capacity of the environment for each wild ungulate species. The introduction of the object e_i allows the annual variation of the maximal capacity. Therefore, one D_i counter exists for each wild ungulate (subscript *i*).

$$r_{e1} \equiv \left(D_{i,j}\right)_{ek} \rightarrow \left(D_{i,j+1}\right)_{ek}, \begin{cases} 1 \leq i \leq w, \\ 0 \leq j \leq 17, \\ 1 \leq k \leq E. \end{cases}$$

4.5.4.2. Ungulate rules

Density regulation module

The object D_i creates objects a_i that represent 90% of the maximal carrying capacity of the environment. To introduce randomness in the process, an object e_i is created representing 20% of the total maximal carrying capacity.

$$r_{e2} \equiv \left(D_{i,18}\right)_{ek} \rightarrow \left(D_{i,19} a_i^{d_{i,k} \cdot 0.9} e_i^{d_{i,k} \cdot 0.2}\right)_{ek}, \begin{cases} 1 \leq i \leq w, \\ 1 \leq k \leq E. \end{cases}$$

$$r_{e3} \equiv \left(D_{i,19}\right)_{ek} \rightarrow \left(D_{i,0}\right)_{ek}, \begin{cases} 1 \leq i \leq w, \\ 1 \leq k \leq E. \end{cases}$$

Objects a_i and e_i are introduced into the membrane labelled as 0 following different probabilities: 1 for the case of a_i and 0.5 for the objects e_i. Thus, the maximal carrying capacity varies annually for each wild grazer.

$$r_{20} \equiv a_i[\quad]_0^0 \rightarrow [a_i]_0^0, 1 \leq i \leq w.$$

$$r_{21} \equiv e_i[\quad]_0^0 \xrightarrow{0.5} [a_i]_0^0, 1 \leq i \leq w.$$

$$r_{22} \equiv e_i[\quad]_0^0 \xrightarrow{0.5} [\quad]_0^0, 1 \leq i \leq w.$$

Reproduction module

When the charge of membrane 1 changes to $+$ objects X_{ij} and XA_{ij}, associated with wild and domestic animals, respectively, copy themselves and the copies enter into membrane 1.

$$r_{23} \equiv X_{i,j}[\quad]_1^+ \rightarrow X_{i,j}\left[X_{i,j}\right]_1^0, \begin{cases} 1 \leq j \leq g_{i,5}, \\ 1 \leq i \leq w. \end{cases}$$

$$r_{24} \equiv XA_{i,j}[\quad]_1^+ \rightarrow XA'_{i,j}\left[X_{i,j}\right]_1^0, \begin{cases} 1 \leq j \leq g_{i,5}, \\ w+1 \leq i \leq w+4. \end{cases}$$

The multisets of objects a_i are also introduced into the membrane labelled as 1.

$$r_{25} \equiv a_i[\quad]_1^+ \rightarrow [a_i]_1^0, 1 \leq i \leq w.$$

When the charge of membrane 2 changes to $+$ the objects a_i enter into this membrane.

$$r_{26} \equiv a_i[\quad]_2^+ \rightarrow [a_i]_2^+, 1 \leq i \leq w.$$

In this set of rules the animals reproduce according to their species and age and following given probabilities $p1$, $p2$ and $p3$. The object X_{ij} associated with animals that do not reproduce evolves to Z_{ij}, while the objects associated with reproductive animals change to Z_{ij} and create a new object Z_{i0} of the same species at age 0. In this module, all animals were classified into 5 age classes: (1) young animals, (2) animals that have not yet reached their reproductive age, (3) fertile animals that can reproduce, (4) animals that have exceeded their reproductive age and (5) animals that have reached their average life expectancy. Further distinctions are made within the different classes, employing the following rules:

Young animals:

$$r_{27} \equiv \left[X_{i,j} \rightarrow Z_{i,1}\right]_1^0, \begin{cases} 0 < j < g_{i,2}, \\ 1 \leq i \leq N. \end{cases}$$

Animals that have not yet reached their reproductive age:

$$r_{28} \equiv \left[X_{i,j} \rightarrow Z_{i,2}\right]_1^0, \begin{cases} g_{i,2} \leq j < g_{i,3}, \\ 1 \leq i \leq N. \end{cases}$$

Adult males:

$$r_{29} \equiv \left[X_{i,j} \xrightarrow{p1} Z_{i,3}\right]_1^0, \begin{cases} g_{i,3} \leq j < g_{i,4}, \\ 1 \leq i \leq N. \end{cases}$$

Adult females that reproduce:

$$r_{30} \equiv \left[X_{i,j} \xrightarrow{p2} Z_{i,3} Z_{i,0}^{k_{i,3}}\right]_1^0, \begin{cases} g_{i,3} \leq j < g_{i,4}, \\ 1 \leq i \leq N. \end{cases}$$

Adult females that do not reproduce:

$$r_{31} \equiv \left[X_{i,j} \xrightarrow{p3} Z_{i,3}\right]_1^0, \begin{cases} g_{i,3} \leq j < g_{i,4}, \\ 1 \leq i \leq N. \end{cases}$$

Animals that have exceeded their reproductive age:

$$r_{32} \equiv \left[X_{i,j} \rightarrow Z_{i,4}\right]_1^0, \begin{cases} g_{i,4} \leq j < g_{i,5}, \\ 1 \leq i \leq N. \end{cases}$$

Animals that have reached their average life expectancy:

$$r_{33} \equiv \left[X_{i,g_{i,5}} \rightarrow Z_{i,5}\right]_1^0, 1 \leq i \leq N.$$

Livestock management

Objects associated with domestic ungulates XA'_{ij} leave the skin membrane in order to initiate the livestock increase and reduction processes in the environment.

$$r_{34} \equiv \left[XA'_{i,j}\right]_0^0 \rightarrow XA'_{i,j}[\quad]_0^0, \begin{cases} 0 \leq j \leq g_{i,5}, \\ w+1 \leq i \leq w+4. \end{cases}$$

The increment of the livestock is carried out using an annual probability for each species and the object Ω_s, which controls the year. On the one hand, the objects Ω_s and the animals XA'_{ij} duplicate with a given probability, the so-called increase probability.

$$re_4 \equiv \left(XA'_{i,j}\Omega_s \xrightarrow{inc_{s,i,k}} X\Lambda^2_{i,j}\Omega'^2_s\right)_{ek}, \begin{cases} 1 \leq j \leq g_{i,5}, \\ w+1 \leq i \leq N, \\ 1 \leq k \leq E, \\ 1 \leq s < Y. \end{cases}$$

$$re_5 \equiv \left(XA'_{i,j}\Omega_s \xrightarrow{1-inc_{s,i,k}} X\Lambda_{i,j}\Omega'_s\right)_{ek}, \begin{cases} 1 \leq j \leq g_{i,5}, \\ w+1 \leq i \leq N, \\ 1 \leq k \leq E, \\ 1 \leq s < Y. \end{cases}$$

On the other hand, the objects Λ_{ij} and Ω_s disappear according to their decrease probability. Finally, the subscript of the remaining objects Ω_s increases its value by 1, Ω_{s+1}, representing that one year has passed.

$$re_6 \equiv \left(X\Lambda_{i,j}\Omega'_s \xrightarrow{dec_{s,i,k}}\right)_{ek}, \begin{cases} 1 \leq j \leq g_{i,5}, \\ w+1 \leq i \leq N, \\ 1 \leq k \leq E, \\ 1 \leq s < Y. \end{cases}$$

$$re_7 \equiv \left(X\Lambda_{i,j}\Omega'_s \xrightarrow{1-dec_{s,i,k}} X\Lambda'_{i,j}\Omega_{s+1}\right)_{ek}, \begin{cases} 1 \leq j \leq g_{i,5}, \\ w+1 \leq i \leq N, \\ 1 \leq k \leq E, \\ 1 \leq s < Y. \end{cases}$$

$$re_8 \equiv \left(\Omega_s \xrightarrow{1-inc_{s,i,k}} \Omega_{s+1}\right)_{ek}, \begin{cases} 1 \leq k \leq E, \\ 1 \leq s < Y. \end{cases}$$

The new resulting livestock number is reintroduced into the membrane 0.

$$r_{35} \equiv X\Lambda'_{i,j}[\quad]_0^0 \rightarrow \left[XA_{i,j}\right]_0^0, \begin{cases} 1 \leq j \leq g_{i,5}, \\ w+1 \leq i \leq N. \end{cases}$$

Mortality module

The animals, both livestock and wild, have a different probability to die according to the species and the age. Surviving animals enter into the membrane 2, while dead animals disappear.

Young surviving animals:

$$r_{36} \equiv Z_{i,j}[\quad]_2^+ \xrightarrow{1-\left(m_{i,1}+ht_{i,3}-\left(m_{i,1}ht_{i,3}\right)\right)} \left[Z_{i,j}\right]_2^+, \begin{cases} 0 \le j \le 1, \\ 1 \le i \le N. \end{cases}$$

Young animals that die naturally or by hunting:

$$r_{37} \equiv Z_{i,j}[\quad]_2^+ \xrightarrow{\left(m_{i,1}+ht_{i,3}-\left(m_{i,1}ht_{i,3}\right)\right)} [\quad]_2^+, \begin{cases} 0 \le j \le 1, \\ 1 \le i \le N. \end{cases}$$

Surviving wild adult animals:

$$r_{38} \equiv Z_{i,j}[\quad]_2^+ \xrightarrow{1-p_4} \left[Z_{i,j}\right]_2^+, \begin{cases} 2 \le j \le 5, \\ 1 \le i \le w. \end{cases}$$

Wild adult ungulates that die naturally or by hunting:

$$r_{39} \equiv Z_{i,j}[\quad]_2^+ \xrightarrow{p_4} [\quad]_2^+, \begin{cases} 2 \le j \le 5, \\ 1 \le i \le w. \end{cases}$$

Surviving adult livestock:

$$r_{40} \equiv Z_{i,j}[\quad]_2^+ \xrightarrow{1-m_{i,2}} \left[Z_{i,j}\right]_2^+, \begin{cases} 2 \le j \le 5, \\ w+1 \le i \le N. \end{cases}$$

Dead adult livestock:

$$r_{41} \equiv Z_{i,j}[\quad]_2^+ \xrightarrow{m_{i,2}} [\quad]_2^+, \begin{cases} 2 \le j \le 5, \\ w+1 \le i \le N. \end{cases}$$

Grazing module I

The grazing module comprises two parts. Firstly, cows and horses graze flat zones (moderate and gentle slopes) and, secondly, the other domestic animals and the wild ungulates graze all available grazing land. Moreover, the probability pf_{lis} controls the surfaces where the ungulates can graze. When cows and horses find accessible forage to cover their energetic requirements G'_{ls}, the objects associated with the animals dissolve and remains only the objects representing consumed forage GC_{ls} outside membrane 2. Meanwhile the rest of objects that represent goats, sheep and wild ungulates, pass from Z_{ij} to Z'_{ij} and prepare to graze.

$$r_{42} \equiv \left[Z_{i,j}{G'}_{l,s}^{f_i}\right]_2^+ \xrightarrow{pf_{l,i,s}} GC_{l,s}^{f_i}[\quad]_2^+, \begin{cases} 1 \le j \le 5, \\ w+3 \le i \le N, \\ 1 \le l \le LU, \\ 1 \le s \le 2. \end{cases}$$

$$r_{43} \equiv \left[Z_{i,j} \rightarrow {Z''}_{i,j}\right]_2^+, \begin{cases} 0 \le j \le 5, \\ 1 \le i \le w+2. \end{cases}$$

$$r_{44} \equiv \left[GC_{l,s}\right]_1^0 \rightarrow {GC'}_{l,s}GC_{l,s}[\quad]_1^0, \begin{cases} 1 \le l \le LU, \\ 1 \le s \le 2. \end{cases}$$

Sheep and goats graze after cattle and horses. The only difference between the two grazing processes regards the probability: small livestock (subscripts $w+1$ and $w+2$) can graze on all slopes while cows and horses (subscripts $w+3$ and N) can only graze on moderate slopes.

$$r_{45} \equiv \left[Z''_{i,j} G'^{f_i}_{l,s}\right]_2^+ \xrightarrow{pf_{l,i,s}} GC^{f_i}_{l,s} [\quad]_2^-, \begin{cases} w+1 \le i \le w+2, \\ 1 \le j \le 5, \\ 1 \le l \le LU, \\ 1 \le s \le 2. \end{cases}$$

When the wild ungulates graze, they do not disappear but they evolve into new objects V_{ij}, which represent animals that have been fed. The objects V_{ij} and the consumed grass GC_{ls} abandon membrane 2 and enter membrane 1.

$$r_{46} \equiv \left[Z''_{i,j} a_i G'^{f_i}_{l,s}\right]_2^+ \xrightarrow{pf_{l,i,s}} V_{i,j} GC^{f_i}_{l,s} [\quad]_2^-, \begin{cases} 1 \le i \le w, \\ 0 \le j < 5, \\ 1 \le l \le LU, \\ 1 \le s \le 2. \end{cases}$$

Wild ungulates that have reached the average life expectancy

$$r_{47} \equiv \left[Z''_{i,5} a_i G'^{f_i}_{l,s}\right]_2^+ \xrightarrow{pf_{l,i,s}} GC^{f_i}_{l,s} [\quad]_2^-, \begin{cases} 1 \le i \le w, \\ 1 \le l \le LU, \\ 1 \le s \le 2. \end{cases}$$

Environment changes

All the objects that have not participated in the grazing processes –animals without enough feed or space, remaining density regulation objects and produced grass– abandon membrane 2. These objects move to the virtual environment ($E+1$), where the grazing process is repeated.

$$r_{48} \equiv \left[Z''_{i,j}\right]_2^- \to Z'_{i,j} [\quad]_2^0, \begin{cases} 1 \le i \le w, \\ 0 \le j \le 5. \end{cases}$$

$$r_{49} \equiv \left[Z''_{i,j}\right]_2^- \to Z'_{i,j} [\quad]_2^0, \begin{cases} w+1 \le i \le w+2, \\ 1 \le j \le 5. \end{cases}$$

$$r_{50} \equiv \left[Z_{i,j}\right]_2^- \to Z'_{i,j} [\quad]_2^0, \begin{cases} w+3 \le i \le N, \\ 1 \le j \le 5. \end{cases}$$

$$r_{51} \equiv [a_i]_2^- \to a'_i [\quad]_2^0, 1 \le i \le w.$$

$$r_{52} \equiv \left[G'_{l,s}\right]_2^- \to G''_{l,s} [\quad]_2^0, \begin{cases} 1 \le l \le LU, \\ 1 \le s \le 2. \end{cases}$$

The objects of age 0, representing the offspring of the year, dissolve, because they do not participate in the grazing process.

$$r_{53} \equiv \left[Z''_{i,0}\right]_2^- \to Z'_{i,j} [\quad]_2^0, w+1 \le i \le w+2.$$

$$r_{54} \equiv \left[Z_{i,0}\right]_2^- \to [\quad]_2^0, w+3 \le i \le N.$$

The wild animals that have grazed pass from membrane 1 to membrane 0.

$$r_{55} \equiv \left[V_{i,j}\right]_1^0 \rightarrow V_{i,j}\left[\quad\right]_1^0, \begin{cases} 0 \leq j < 5, \\ 1 \leq i \leq N. \end{cases}$$

In membrane 0, produced and consumed grass objects form pairs and dissolve until no more consumed grass objects are left. This rule allows counting the amount of grass that is not consumed by animals.

$$r_{56} \equiv \left[GS_{l,a,s} GC'_{l,s} \rightarrow\right]_0^0, \begin{cases} 1 \leq l \leq LU, \\ 1 \leq a \leq h, \\ 1 \leq s \leq 2. \end{cases}$$

Objects associated with animals that have not fed and not consumed resources (i.e. space and forage) leave, firstly, the membrane 1 and, secondly, the membrane 0, coming to a temporary rest in the environment.

$$r_{57} \equiv [a'_i]_1^0 \rightarrow a'_i\,[\quad]_1^0, 1 \leq i \leq w.$$

$$r_{58} \equiv \left[G''_{l,s}\right]_1^0 \rightarrow G''_{l,s}\left[\quad\right]_1^0, \begin{cases} 1 \leq l \leq LU, \\ 1 \leq s \leq 2. \end{cases}$$

$$r_{59} \equiv \left[Z'_{i,j}\right]_1^0 \rightarrow Z'_{i,j}\left[\quad\right]_1^0, \begin{cases} 1 \leq i \leq N, \\ 0 \leq j \leq 5. \end{cases}$$

$$r_{60} \equiv [a'_i]_0^0 \rightarrow a'_i\,[\quad]_0^0, 1 \leq i \leq w.$$

$$r_{61} \equiv \left[G''_{l,s}\right]_0^0 \rightarrow G''_{l,s}\left[\quad\right]_0^0, \begin{cases} 1 \leq l \leq LU, \\ 1 \leq s \leq 2. \end{cases}$$

$$r_{62} \equiv \left[Z'_{i,j}\right]_0^0 \rightarrow Z'_{i,j}\left[\quad\right]_0^0, \begin{cases} 1 \leq i \leq N, \\ 0 \leq j \leq 5. \end{cases}$$

In the environment, these objects acquire a new subscript k that contains information about the source environment.

$$re_9 \equiv \left(a'_i \rightarrow aE_{i,k}\right)_{ek}, \begin{cases} 1 \leq i \leq w, \\ 1 \leq k \leq E. \end{cases}$$

$$re_{10} \equiv \left(G''_{l,s} \rightarrow GE_{l,s,k}\right)_{ek}, \begin{cases} 1 \leq l \leq LU, \\ 1 \leq s \leq 2, \\ 1 \leq k \leq E. \end{cases}$$

$$re_{11} \equiv \left(Z'_{i,j} \rightarrow ZE_{i,j,k}\right)_{ek}, \begin{cases} 1 \leq i \leq N, \\ 0 \leq j \leq 5, \\ 1 \leq k \leq E. \end{cases}$$

Afterwards, the objects leave the environment and move to the virtual environment $(E+1)$.

$$re_{12} \equiv \left(\left(aE_{i,k}\right)_{ek}\left(\quad\right)_{e(E+1)} \rightarrow \left(\quad\right)_{ek}\left(aE'_{i,k}\right)_{e(E+1)}\right)_p, \begin{cases} 1 \leq i \leq w, \\ 1 \leq k \leq E. \end{cases}$$

$$re_{13} \equiv \left(\left(GE_{l,s,k}\right)_{ek}\left(\quad\right)_{e(E+1)} \rightarrow \left(\quad\right)_{ek}\left(GE'_{l,s,k}\right)_{e(E+1)}\right)_p, \begin{cases} 1 \leq l \leq LU, \\ 1 \leq s \leq 2, \\ 1 \leq k \leq E. \end{cases}$$

$$re_{14} \equiv \left(\left(ZE_{i,j,k} \right)_{ek} (\quad)_{e(E+1)} \rightarrow (\quad)_{ek} \left(ZE'_{i,j,k} \right)_{e(E+1)} \right)_p, \begin{cases} 1 \leq i \leq N, \\ 0 \leq j \leq 5, \\ 1 \leq k \leq E. \end{cases}$$

Finally, the three types of objects, ungulates, space and forage, reach the membrane 0 of the virtual environment $(E+1)$. In this region, the environment change is simulated, whereat the objects representing ungulates try to use the objects representing resources from other environments.

$$r_{63} \equiv aE'_{i,k}[\quad]_0^0 \rightarrow \left[aE'_{i,k} \right]_0^0, \begin{cases} 1 \leq i \leq w, \\ 1 \leq k \leq E. \end{cases}$$

$$r_{64} \equiv GE'_{l,s,k}[\quad]_0^0 \rightarrow \left[GE'_{l,s,k} \right]_0^0, \begin{cases} 1 \leq l \leq LU, \\ 1 \leq s \leq 2, \\ 1 \leq k \leq E. \end{cases}$$

$$r_{65} \equiv ZE'_{i,j,k}[\quad]_0^0 \rightarrow \left[ZE'_{i,j,k} \right]_0^0, \begin{cases} 1 \leq i \leq N, \\ 0 \leq j \leq 5, \\ 1 \leq k \leq E. \end{cases}$$

Grazing module II

In the following rules, the grazing process is repeated. The steps are the same as in the previous feeding process: first graze cows and horses on moderate and gentle slopes and afterwards the other livestock and wild ungulates on all the available surfaces. Wild ungulates change their environment subscript according to the environment in which they have fed.

Cattle and horses:

$$r_{66} \equiv \left[ZE'_{i,j,u} GE'^{f_i}_{l,s,v} \right]_0^0 \xrightarrow{pm_{i,u,v}\, pf_{l,i,s}} \left[GCE'^{f_i}_{l,s,v} \right]_0^0, \begin{cases} w+3 \leq i \leq N, \\ 0 \leq j \leq 5, \\ 1 \leq l \leq LU, \\ 1 \leq s \leq 2, \\ 1 \leq u \leq E, \\ 1 \leq v \leq E. \end{cases}$$

$$r_{67} \equiv \left[ZE'_{i,j,k} \rightarrow ZE''_{i,j,k} \right]_0^0, \begin{cases} 1 \leq i \leq w+2, \\ 0 \leq j \leq 5, \\ 0 \leq k \leq E. \end{cases}$$

Sheep and goats:

$$r_{68} \equiv \left[ZE''_{i,j,u} GE'^{f_i}_{l,s,v} \right]_0^0 \xrightarrow{pm_{i,u,v}\, pf_{l,i,s}} GCE^{f_i}_{l,s,v} [\quad]_0^0, \begin{cases} w+1 \leq i \leq w+2, \\ 0 \leq j \leq 5, \\ 1 \leq l \leq LU, \\ 1 \leq s \leq 2, \\ 1 \leq u \leq E, \\ 1 \leq v \leq E. \end{cases}$$

Wild ungulates:

$$r_{69} \equiv \left[ZE''_{i,j,u}aE'_{i,v}GE'^{f_i}_{l,s,v}\right]^0_0 \xrightarrow{pm_{i,u,v}\,pf_{l,i,s}} WE_{i,j,v}GCE^{f_i}_{l,s,v}\,[\quad]^0_0, \begin{cases} 1 \le i \le w, \\ 0 \le j < 5, \\ 1 \le l \le LU, \\ 1 \le s \le 2, \\ 1 \le u \le E, \\ 1 \le v \le E. \end{cases}$$

Wild ungulates that have reached the limit of their life expectancy:

$$r_{70} \equiv \left[ZE''_{i,5,u}aE'_{i,v}GE'^{f_i}_{l,s,v}\right]^0_0 \xrightarrow{pm_{i,u,v}\,pf_{l,i,s}} GCE^{f_i}_{l,s,v}\,[\quad]^0_0, \begin{cases} 1 \le i \le w, \\ 1 \le l \le LU, \\ 1 \le s \le 2, \\ 1 \le u \le E, \\ 1 \le v \le E. \end{cases}$$

Grass or forage consumed by cattle and horses GCE'_{lsv} turns into general grass consumed by GCE_{lsv}.

$$r_{71} \equiv \left[GCE'_{l,s,v}\right]^0_0 \rightarrow GCE_{l,s,v}\,[\quad]^0_0, \begin{cases} 1 \le l \le LU, \\ 1 \le s \le 2, \\ 1 \le v \le E. \end{cases}$$

A membrane charge allows dissolving the objects that are not used in grazing.

$$r_{72} \equiv aE'_{i,k}[\quad]^+_3 \rightarrow [\quad]^0_3, \begin{cases} 1 \le i \le w, \\ 1 \le k \le E. \end{cases}$$

$$r_{73} \equiv GE'_{l,s,k}[\quad]^+_3 \rightarrow [\quad]^0_3, \begin{cases} 1 \le l \le LU, \\ 1 \le s \le 2, \\ 1 \le k \le E. \end{cases}$$

$$r_{74} \equiv ZE'_{i,j,k}[\quad]^+_3 \rightarrow [\quad]^0_3, \begin{cases} w+3 \le i \le N, \\ 0 \le j \le 5, \\ 1 \le k \le E. \end{cases}$$

$$r_{75} \equiv ZE''_{i,j,k}[\quad]^+_3 \rightarrow [\quad]^0_3, \begin{cases} 1 \le i \le w+2, \\ 0 \le j \le 5, \\ 1 \le k \le E. \end{cases}$$

Objects that represent animals that have grazed WE_{ijk} in another environment and objects that represent the quantity of grass consumed GSE_{lsk} leave the virtual environment $(E+1)$ and move to the environment from which they have obtained forage and space (resources).

$$re_{15} \equiv \left(\left(WE_{i,j,k}\right)_{e(E+1)}(\quad)_{ek} \rightarrow (\quad)_{e(E+1)}\left(WE'_{i,j}\right)_{ek}\right)_p, \begin{cases} 1 \le i \le w, \\ 0 \le j < 5, \\ 1 \le k \le E. \end{cases}$$

$$re_{16} \equiv \left(\left(GCE_{l,s,k}\right)_{e(E+1)}(\quad)_{ek} \rightarrow (\quad)_{e(E+1)}\left(GCE'_{l,s}\right)_{ek}\right)_p, \begin{cases} 1 \le l \le LU, \\ 1 \le s \le 2, \\ 1 \le k \le E. \end{cases}$$

When the objects representing animals enter into the membrane 0 of their corresponding environment, they change into V_{ij}.

$$r_{76} \equiv WE'_{i,j}[\quad]_0^0 \rightarrow [V_{i,j}]_0^0, \begin{cases} 1 \le i \le w, \\ 0 \le j < 5. \end{cases}$$

An object that represents the consumed grass creates two new objects GC_{ls} and GC'_{ls}.

$$r_{77} \equiv GCE'_{l,s}[\quad]_0^0 \rightarrow [GC_{l,s}GC'_{l,s}]_0^0, \begin{cases} 1 \le l \le LU, \\ 1 \le s \le 2. \end{cases}$$

Objects that represent the initial animals change to Y_{ij} in the membrane 3.

$$r_{78} \equiv X_{i,j}[\quad]_3^- \rightarrow [Y_{i,j}]_3^0, \begin{cases} 0 \le j \le g_{i,5}, \\ 1 \le i \le N. \end{cases}$$

The wild animals enter into the membrane 3, too.

$$r_{79} \equiv V_{i,j}[\quad]_3^- \rightarrow [V_{i,j}]_3^0, \begin{cases} 0 \le j < 5, \\ 1 \le i \le N. \end{cases}$$

The newborn wild animals move from membrane 3 to the skin membrane and change their age into 1.

$$r_{80} \equiv [V_{i,0}]_3^0 \rightarrow X_{i,1}[\quad]_3^+, 1 \le i \le w.$$

In the following set of rules, the wild animals that have grazed V_{ij} form pairs with the objects Y_{ij} and change into initial objects X_{ij}, increasing their age by 1 year, that is to say that the subscript j increases one unit.

$$r_{81} \equiv [V_{i,1}Y_{i,j}]_3^0 \rightarrow X_{i,j+1}[\quad]_3^+, \begin{cases} 0 < j < g_{i,2}, \\ 1 \le i \le w. \end{cases}$$

$$r_{82} \equiv [V_{i,2}Y_{i,j}]_3^0 \rightarrow X_{i,j+1}[\quad]_3^+, \begin{cases} g_{i,2} \le j < g_{i,3}, \\ 1 \le i \le w. \end{cases}$$

$$r_{83} \equiv [V_{i,3}Y_{i,j}]_3^0 \rightarrow X_{i,j+1}[\quad]_3^+, \begin{cases} g_{i,3} \le j < g_{i,4}, \\ 1 \le i \le w. \end{cases}$$

$$r_{84} \equiv [V_{i,4}Y_{i,j}]_3^0 \rightarrow X_{i,j+1}[\quad]_3^+, \begin{cases} g_{i,4} \le j < g_{i,5}, \\ 1 \le i \le w. \end{cases}$$

The wild animals that have reached the limit of their life expectancy disappear.

$$r_{85} \equiv [V_{i,5}]_3^0 \rightarrow [\quad]_3^+, 1 \le i \le w.$$

Finally, the remaining objects Y_{ij} that have not found objects representing wild animals that have been fed V_{ij}, dissolve.

$$r_{86} \equiv [Y_{i,j}]_3^+ \rightarrow [\quad]_3^0, \begin{cases} 0 < j \le g_{i,5}, \\ 1 \le i \le w. \end{cases}$$

4.5.4.3. Land-use rules

Forage production

Environment randomness regarding the length of the growing season and forage production is introduced into the model by means of the object TR, created in rule 5. In the environment 1 this object leaves the membrane 0 and moves to the environment where it creates objects WN_{isk} for all environments (E) equally, containing the same information. As soon as these new objects WN_{isk} exist, they replace the objects TR in the other environments.

$$r_{87} \equiv [TR]_0^0 \rightarrow TR[\quad]_0^0.$$

$$re_{17} \equiv \left(TR \xrightarrow{1/100} WN_{i,j,1}, WN_{i,j,2}, \dots, WN_{i,j,E},\right)_{e1}, \begin{cases} 1 \leq i \leq 10, \\ 1 \leq j \leq 10. \end{cases}$$

$$re_{18} \equiv \left(TR \rightarrow\right)_{ek}, 2 \leq k \leq E.$$

One of the objects WN_{ijk} is sent to each other environments as WN'_{ijk}. This ensures that the same conditions apply in all environments. The WN_{ijk} object remaining in environment 1 evolves into a WN'_{ijk}. Once in their environment, these objects change into objects N_{ij}, one per hectare of the environment (δ). Each N_{ij} interacts with a surface unit (ha) of a land use in order to produce new available forage.

$$re_{19} \equiv \left(\left(WN_{i,j,k}\right)_{e1}(\quad)_{ek} \rightarrow (\quad)_{e1}\left(WN'_{i,j,k}\right)_{ek}\right)_p, \begin{cases} 1 \leq i \leq 10, \\ 1 \leq j \leq 10. \\ 1 \leq k \leq E \end{cases}$$

$$re_{20} \equiv \left(WN_{i,j,1} \rightarrow WN'_{i,j,1}\right)_{e1}, \begin{cases} 1 \leq i \leq 10, \\ 1 \leq j \leq 10. \end{cases}$$

$$re_{21} \equiv \left(WN'_{i,j,k} \rightarrow N_{i,j}^{\delta_k}\right)_{ek}, \begin{cases} 1 \leq i \leq 10, \\ 1 \leq j \leq 10, \\ 1 \leq k \leq 2. \end{cases}$$

In the following set of rules the objects N_{ij} and A_{las} enter into the membrane 0 where the forage production process takes (rule 90). When the object N_{ij} finds an object A_{las} they produce a certain amount of objects φ_{las} (kg DM ha^{-1} year^{-1}) with a given probability ($prod_{laij}$) according to the type of land use, the altitude, the slope and the values of the subscripts provided by the object N_{ij}.

$$r_{88} \equiv N_{i,j}[\quad]_0^0 \rightarrow \left[N_{i,j}\right]_0^0, \begin{cases} 1 \leq i \leq 10, \\ 1 \leq j \leq 10. \end{cases}$$

$$r_{89} \equiv \left[A_{l,a,s}\right]_1^0 \rightarrow A_{l,a,s}[\quad]_1^0, \begin{cases} 1 \leq l \leq LU, \\ 1 \leq a \leq h, \\ 1 \leq s \leq 2. \end{cases}$$

$$r_{90} \equiv \left[N_{i,j} A_{l,a,s} \rightarrow \varphi_{l,a,s}^{(prod_{l,a,i,j})} A_{l,a,s}\right]_0^0, \begin{cases} 1 \leq l \leq LU, \\ 1 \leq a \leq h, \\ 1 \leq s \leq 2, \\ 1 \leq i \leq 10, \\ 1 \leq j \leq 10. \end{cases}$$

The total forage production outside of the positively charged membrane produces two objects G_{las} and G'_{ls} that retain the same information in the membrane 1.

$$r_{91} \equiv \varphi_{l,a,s}[\quad]_1^+ \rightarrow [G_{l,a,s}G'_{l,s}]_1^0, \begin{cases} 1 \leq l \leq LU, \\ 1 \leq a \leq h, \\ 1 \leq s \leq 2. \end{cases}$$

$$r_{92} \equiv G'_{l,s}[\quad]_2^+ \rightarrow [G'_{l,s}]_2^+, \begin{cases} 1 \leq l \leq LU, \\ 1 \leq s \leq 2. \end{cases}$$

$$r_{93} \equiv [G_{l,a,s}]_1^0 \rightarrow G_{l,a,s}GS_{l,a,s}[\quad]_1^0, \begin{cases} 1 \leq l \leq LU, \\ 1 \leq a \leq h, \\ 1 \leq s \leq 2. \end{cases}$$

Forest Fire

This module is only available in the application for the Pyrenees. The grassland recovery process due to natural forest fires begins with the object ff created in rule 2. This object can disappear or not with a given probability of 50%. In the case that the object remains in the system, it creates randomly new objects that contain information about the number of hectares that will be burned, both for tree vegetation or forest ft and for shrub vegetation fs. This burned surface is not restricted to the study area, as a fire can affect the whole administrative district.

$$r_{94} \equiv \left[ff \xrightarrow{\left(\frac{1}{100}\right)} ft^{treefire_v} fs^{shrubfire_v}, ba_v \right]_0^0, 1 \leq v \leq 50.$$

$$r_{95} \equiv [ff]_0^0 \xrightarrow{\frac{1}{2}} [\quad]_0^0.$$

On the one hand, objects ft and fs can find objects associated with a land-use surface within the study area. When this happens, the affected surfaces burn and evolve into grassland.

$$r_{96} \equiv \left[A_{forest,a,s} ft \rightarrow A_{grassland,a,s} \right]_0^0, \begin{cases} 1 \leq a \leq h, \\ 1 \leq s \leq 2. \end{cases}$$

$$r_{97} \equiv \left[A_{shrubland,a,s} fs \rightarrow A_{grassland,a,s} \right]_0^0, \begin{cases} 1 \leq a \leq h, \\ 1 \leq s \leq 2. \end{cases}$$

On the other hand, the objects representing the forest fire can find a surface not included in the study area, in this case the objects simply dissolve.

$$r_{98} \equiv \left[T, ft \rightarrow T \right]_0^0.$$

$$r_{99} \equiv \left[S, fs \rightarrow S \right]_0^0.$$

Finally, the auxiliary object ba_v, created in this module, dissolves.

$$r_{100} \equiv [ba_v]_0^0 \rightarrow [\quad]_0^0.$$

Abandonment

When none of the produced forage corresponding to one hectare of a land use placed in a determinate altitude a and a slope s (A_{ias}) is consumed by the ungulates, this hectare evolves into abandoned land with a given ratio Ab ($Ab = 4$).

$$r_{101} \equiv GS_{grassland,a,s}^{(Ab \cdot ug_l \cdot \mu T_{l,a} \cdot \mu R_l)} A_{grassland,a,s}[\quad]_1^- \rightarrow [A_{abandoned,a,s}]_1^0, \begin{cases} 1 \leq l \leq LU, \\ 1 \leq a \leq h, \\ 1 \leq s \leq 2. \end{cases}$$

Reforestation

In this work, the reforestation process is differentiated for the two study areas. In the Pyrenees the reforestation process is carried out in two steps: abandoned land can evolve into shrubland and this can evolve into forest with (rps) and (rpf) probabilities, respectively. In the Alps, the abandoned landscape can be colonized by forest by means of a reforestation probability (rpa) depending on the altitudinal range a.

Pyrenees

$$r_{102} \equiv A_{abandoned,a,s}[\quad]_1^- \xrightarrow{rp_s} [A_{shrubland,a,s}]_1^0, \begin{cases} 1 \leq a \leq h, \\ 1 \leq s \leq 2. \end{cases}$$

$$r_{103} \equiv A_{abandoned,a,s}[\quad]_1^- \xrightarrow{1-rp_s} [A_{abandoned,a,s}]_1^0, \begin{cases} 1 \leq a \leq h, \\ 1 \leq s \leq 2. \end{cases}$$

$$r_{104} \equiv A_{shrubland,a,s}[\quad]_1^- \xrightarrow{rp_f} [A_{forest,a,s}]_1^0, \begin{cases} 1 \leq a \leq h, \\ 1 \leq s \leq 2. \end{cases}$$

$$r_{105} \equiv A_{shrubland,a,s}[\quad]_1^- \xrightarrow{1-rp_f} [A_{shrubland,a,s}]_1^0, \begin{cases} 1 \leq a \leq h, \\ 1 \leq s \leq 2. \end{cases}$$

Alps

$$r_{106} \equiv A_{abandoned,a,s}[\quad]_1^- \xrightarrow{rp_a} [A_{forest,a,s}]_1^0, \begin{cases} 1 \leq a \leq h, \\ 1 \leq s \leq 2. \end{cases}$$

$$r_{107} \equiv A_{abandoned,a,s}[\quad]_1^- \xrightarrow{1-rp_a} [A_{abandoned,a,s}]_1^0, \begin{cases} 1 \leq a \leq h, \\ 1 \leq s \leq 2. \end{cases}$$

Update module

Finally, the update module is executed. These rules serve to recover the initial configuration to start a new cycle. When the charge of membrane 3 changes from negative to null, all the remaining objects related to forage produced in the current cycle disappear or change into new objects GF_{ls}, total grass consumed and G'_{las} total grass produced to be accounted in the model.

$$r_{108} \equiv GC'_{l,s}[\quad]_3^- \rightarrow [\quad]_3^0, \begin{cases} 1 \leq l \leq LU, \\ 1 \leq s \leq 2. \end{cases}$$

$$r_{109} \equiv GC_{l,s}[\quad]_3^- \rightarrow [GF_{l,s}]_3^0, \begin{cases} 1 \leq l \leq LU, \\ 1 \leq s \leq 2. \end{cases}$$

$$r_{110} \equiv G_{l,a,s}[\quad]_3^- \rightarrow [GP_{l,a,s}]_3^0, \begin{cases} 1 \leq l \leq LU, \\ 1 \leq a \leq h, \\ 1 \leq s \leq 2. \end{cases}$$

$$r_{111} \equiv GS_{l,a,s}[\quad]_3^- \rightarrow [\quad]_3^0, \begin{cases} 1 \le l \le LU, \\ 1 \le a \le h, \\ 1 \le s \le 2. \end{cases}$$

A new charge change in membrane 3 enables the objects GF_{ls} and G'_{las} to move from membrane 3 to 0 and to disappear at the beginning of a new cycle.

$$r_{112} \equiv \left[GF_{l,s}\right]_3^0 \rightarrow GF_{l,s}\,[\quad]_3^+, \begin{cases} 1 \le l \le LU, \\ 1 \le s \le 2. \end{cases}$$

$$r_{113} \equiv \left[GP_{l,a,s}\right]_3^0 \rightarrow \left[GP_{l,a,s}\right]_3^+, \begin{cases} 1 \le l \le LU, \\ 1 \le a \le h, \\ 1 \le s \le 2. \end{cases}$$

$$r_{114} \equiv GP_{l,a,s}[\quad]_3^+ \rightarrow [\quad]_3^0, \begin{cases} 1 \le l \le LU, \\ 1 \le a \le h, \\ 1 \le s \le 2. \end{cases}$$

$$r_{115} \equiv GF_{l,s}[\quad]_3^+ \rightarrow [\quad]_3^0, \begin{cases} 1 \le l \le LU, \\ 1 \le s \le 2. \end{cases}$$

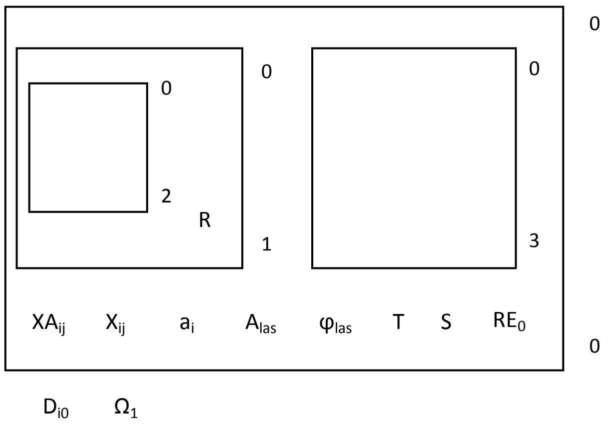
To conclude this point, table 6 displays a resume of the membrane number, alphabet size and total evolution rules, for each study area.

Table 6: Summary of the total number of components in the PDP model for each study area

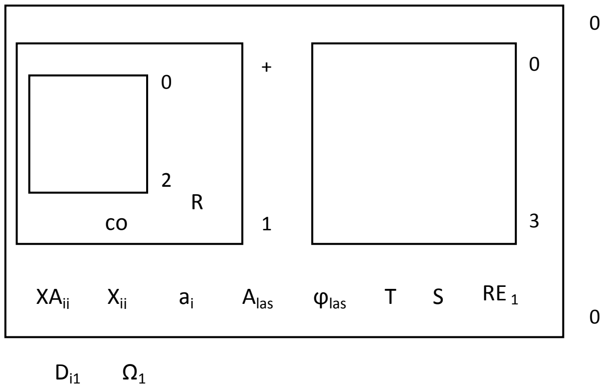
Study case	Environments	Membranes	Alphabet size	Evolution rules
Stubai Valley	2	16	2223	23082
Catalan Pyrenees	9	51	4286	78519

4.6. Execution of a cycle of the model

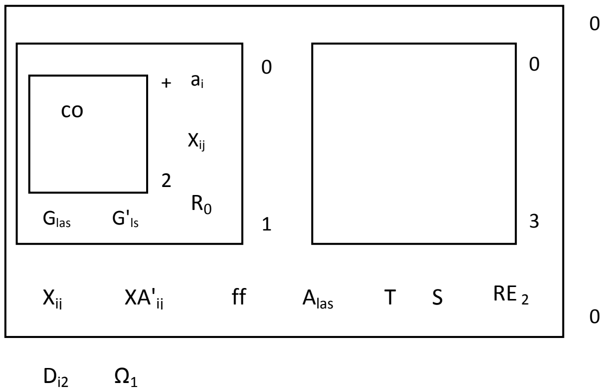
The execution of a cycle (Figure 15) involves 20 configuration steps, representing the time span in which the vegetation grows and the ungulates graze on the alpine and subalpine pastures. All the counters are represented in each configuration, regardless of whether it is a physical or a virtual environment.



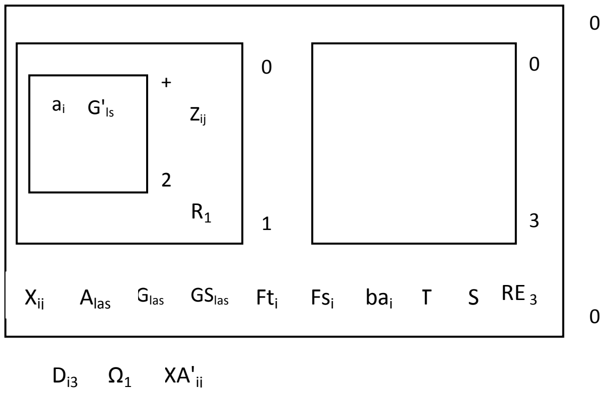
Configuration 0: The XA_{ij} objects are associated with domestic animals and X_{ij} objects with wild animals. The subscript *i* represents the species and *j* the age. A_{las} represents the land use *l* in a determinate altitude *a* and slope range *s*. Object φ is the amount of forage available for grazing. *R*, *RE* and D_i are counters. Ω_y controls the year in the increase or decrease of domestic animals. *T* and *S* represent the forest and shrub surface outside the study area.



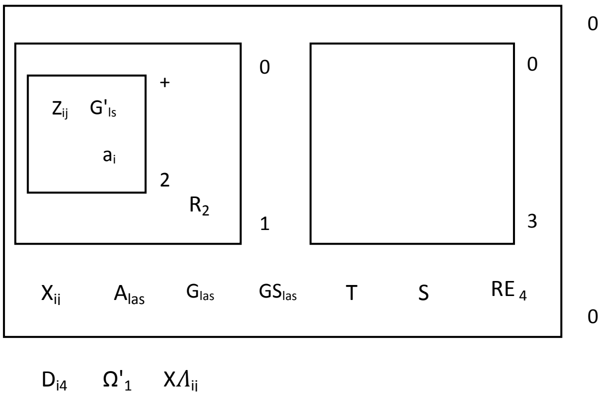
Configuration 1: An object *co* appears in membrane 1 and the charge of this membrane changes to +.



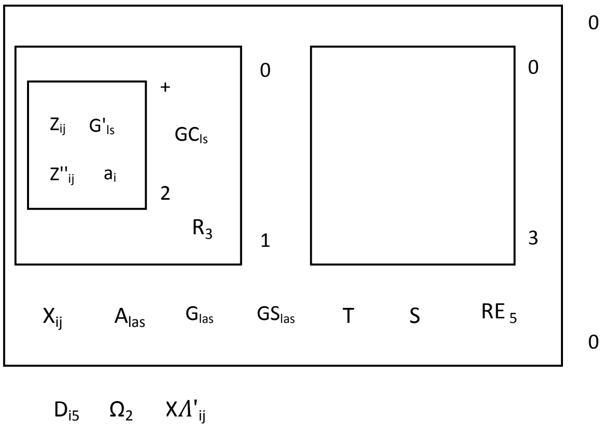
Configuration 2: The object *co* enters into membrane 2 and changes its charge into +. Objects X_{ij} and XA_{ij} copy themselves and enter into membrane 1. Object φ_{las} creates new objects G_{las} and G'_{ls}, which enter into membrane 1. Object a_i, related to the density regulation, enters in membrane 1. An object *ff* can be created to begin the forest fire process.



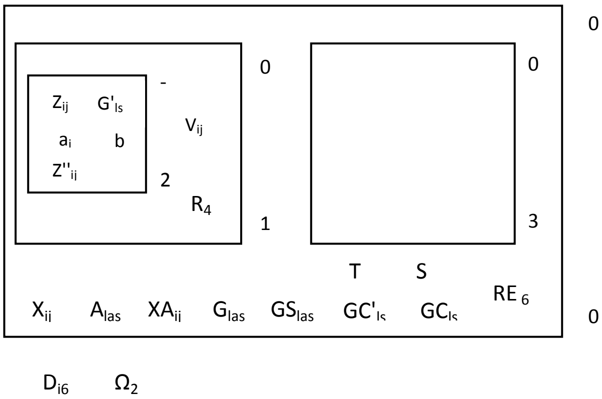
Configuration 3: The objects XA'_{ij} leave the skin membrane. Objects a_i and G'_{ls} enter into membrane 2. Objects representing animals reproduce and change into objects Z_{ij}. The grass object creates two new objects G_{las} and GS_{las} in the skin membrane, which contain the available forage. Object *ff* evolves into the objects Ft_i and Fs_i containing the burned surface information.



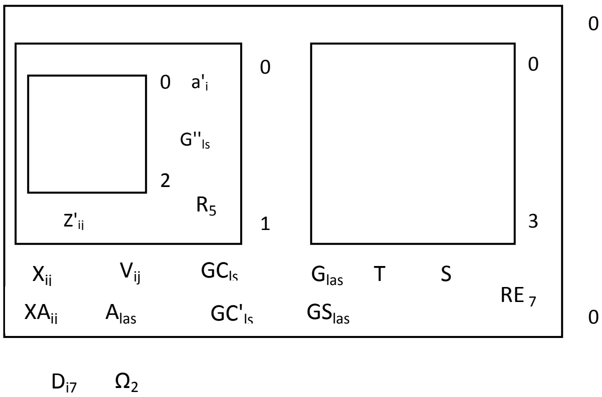
Configuration 4: The increase of domestic animals occurs outside of the skin membrane, where an object $XΛ_{ij}$ is created from object XA'_{ij}. This configuration includes the mortality process, whereat the surviving animals are represented by object Z_{ij} within the membrane 2. *ft* and *fs* interact with objects associated with woody surface use, creating grassland surface.



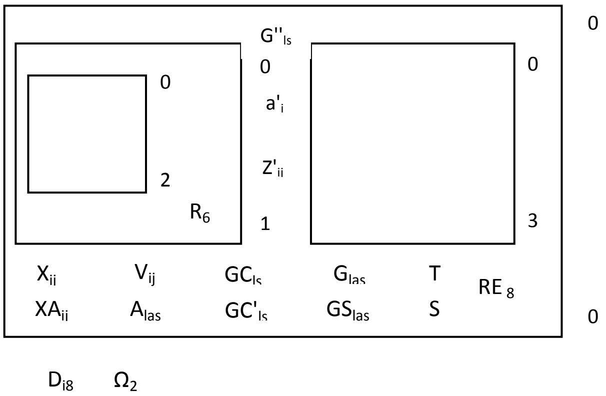
Configuration 5: In this configuration, two processes are carried out: decrease of domestic animals and grazing. The first one occurs outside the skin membrane and determines the final number of animals for the next cycle. Grazing occurs in membrane 2: cattle and horses disappear when they find enough forage and produce a new object GC_{ls} that represents consumed grass. The remaining objects representing animals evolve into Z''_{ij}.



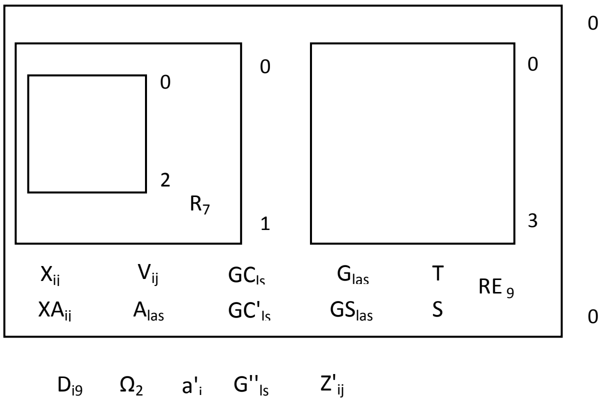
Configuration 6: In membrane 2, sheep, goats and wild ungulates (Z''_{ij}) graze and produce new objects GC_{ls}. In the case of wild ungulates, this reproduction requires furthermore space, represented by the object a_i (density regulation). Finally, the objects associated with wild animals that have grazed evolve into new objects V_{ij} in membrane 1. The objects that have calculated the number of domestic animals for the next cycle XA_{ij} enter into the skin membrane.



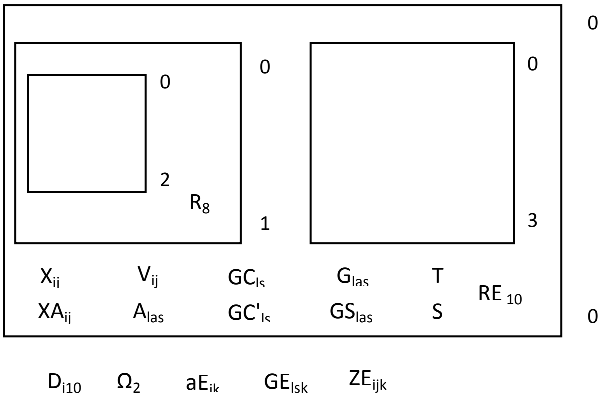
Configuration 7: All objects that have not participated in the grazing process, including animals, objects Z_{ij} and Z''_{ij}, available forage G'_{ls} or space $a'_{i,,}$ leave the membrane 2 and move to 1. The objects associated with wild animals that have grazed V_{ij} enter into the skin membrane.



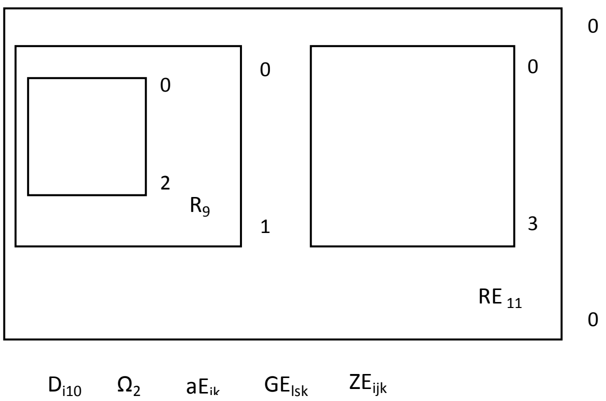
Configuration 8: In this step the rules related to environment changes begin. The objects that have not been consumed in the grazing process and the animals that have not been grazing, objects a'_i, G''_{ls} and Z'_{ij}, leave the membrane 1 and are placed within the skin membrane.



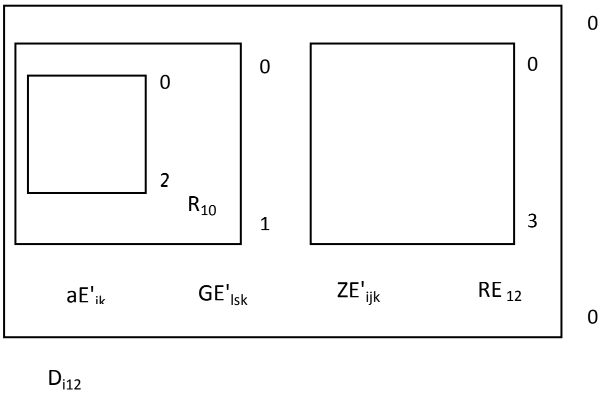
Configuration 9: The same objects mentioned in the previous configuration, density regulation a'_i, available forage G''_{ls} and animals Z'_{ij}, leave the skin membrane.



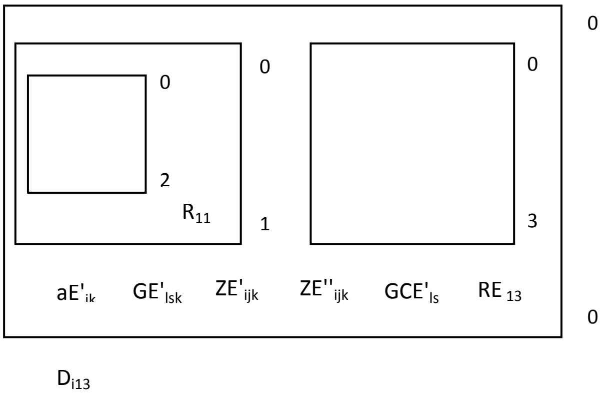
Configuration 10: In this step all objects associated with animals unable to feed, surplus resources, forage and space, prepare to leave their environment. They evolve into new objects aE_{ik}, GE_{lsk} and ZE_{ijk}. The subscript k contains the information from the pertaining environment.



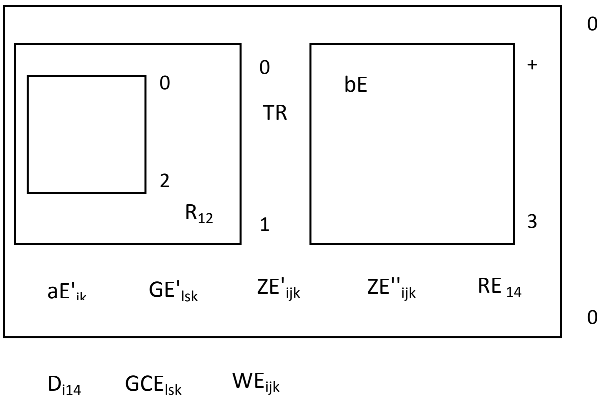
Configuration 11: In this step, all objects associated with animals unable to feed, surplus resources, forage and space, enter into the virtual environment $E+1$.



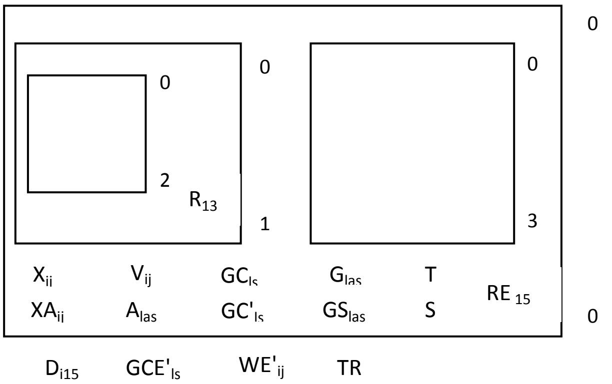
Configuration 12: In this step, objects aE'_{ik}, GE'_{lsk} and ZE'_{ijk} enter into the skin membrane of the virtual environment.



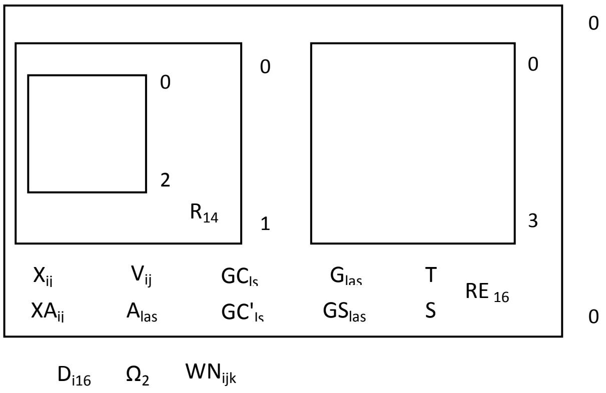
Configuration 13: In the skin membrane the animals try to graze again. First of all, cattle and horses try to graze on moderate slopes. If they can graze, they disappear and produce a new object GCE'_{lsk}, associated with the amount of forage consumed. The remaining animals evolve into ZE''_{ijk}, to prepare for grazing.



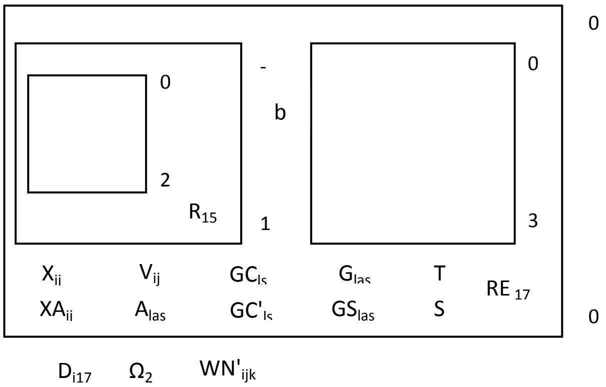
Configuration 14: Given space aE'_{ik} and forage GE'_{lsk}, the objects ZE''_{ijk} produce consumed grass GCE_{lsk} and, in the case of wild ungulates, animals that have satisfied their energetic requirements WE_{ijk}. Both, GCE_{lsk} and WE_{ijk} appear outside the skin membrane. Grass consumed in the previous configuration GCE'_{lsk} evolves into GCE_{lsk}. A *TR* object is created for each environment inside the skin membrane. The *bE* object appears in membrane 3 and changes the charge into +.



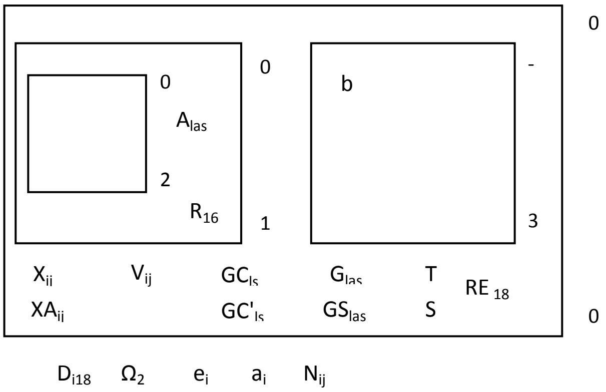
Configuration 15: On the one hand, the WE_{ijk} and GCE_{ls} objects abandon the virtual environment as WE'_{ij} and GCE'_{ls}, returning to the physical environments and all the objects remaining in the virtual environment within the skin membrane are eliminated. On the other hand, in each environment, the object *TR* leaves the skin membrane.



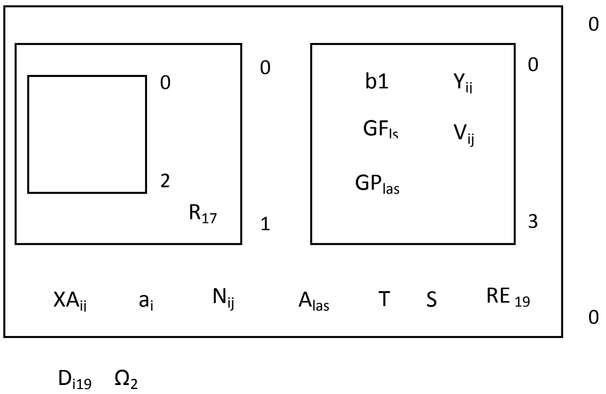
Configuration 16: The objects leaving the virtual environment enter into the skin membrane of their environment, evolving into GC_{ls} and GC'_{ls} in the case of the consumed forage and into V_{ij} in the case of wild ungulates. In parallel, the object *TR* creates a new object WN_{ijk} *that contains the environment variability* in the first environment and disappears in the rest of environments.



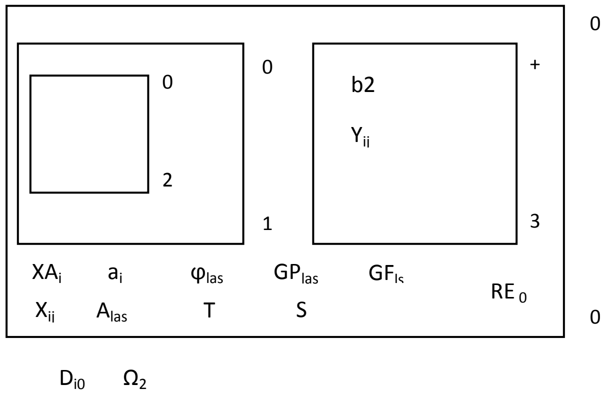
Configuration 17: When an object associated with consumed grass GC'_{ls} finds an object associated with produced grass GS_{las} of the same land use type, slope and altitudinal range, both objects disappear, determining if there has been abandonment. Object WN_{ijk} evolves into WN'_{ijk}. Membrane 1 changes its charge into - and a new object *b* is created.



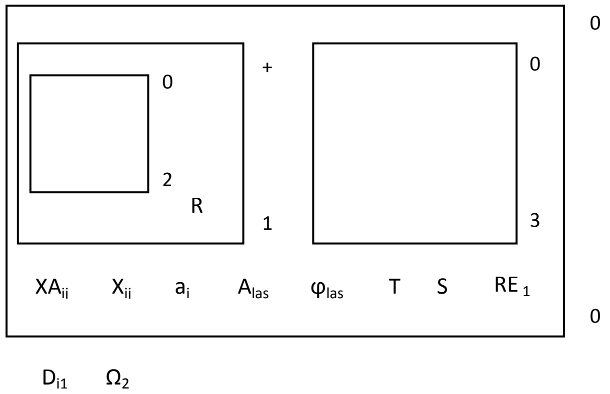
Configuration 18: Objects associated with the land use surface A_{las} enter in membrane 1, evolving into abandoned land, provided that the agricultural intensity is reduced, and into woody vegetation with a given probability changing its charge. Object WN'_{ijk} evolves into object N_{ij}. Object *b* enters in membrane 3, changing its charge into -. Objects a_i and e_i are created to regulate the density of wild animals.



Configuration 19: All objects associated with wild ungulates Y_{ij} and V_{ij},, together with the objects related to consumed and produced forage, enter into membrane 3, evolving into GF_{ls} and GP_{las}. Object a_i is introduced into the skin membrane. Half of the objects enter into the skin membrane, evolving into objects a_i. The objects inside membrane 1 return to the skin membrane. Finally, object N_{ij} enters inside the skin membrane.



Configuration 20: In this configuration, the rules regarding forage production are executed. Each object related to the land use surface A_{las}, produces an amount of forage φ_{las}. The object N_{ij} introduces the variability in forage production and in the length of the growing season. With the change of the charge in membrane 3, the objects GP_{las} and GF_{ls} enter the skin membrane. Finally, a pair of objects Y_{ij} and V_{ij}, which share the same information, create an object X_{ij}, placed in the skin membrane. This configuration corresponds to the initial configuration 0.



Configuration 21: This configuration represents the configuration 1 of a new cycle. GP_{las} and GF_{ls} objects are eliminated as well as all the objects Y_{ij} *that* remain in membrane 3.

4.7. Designing the simulator

To design the computer simulator we use MeCoSim (Pérez-Hurtado et al., 2010). It is a free software tool for simulating biological phenomena by means of P systems, designed by the Natural Computing research group of the University of Seville (http://www.p-linguaorg/mecosim). The inputs and parameters of the model can be introduced directly into an interface of the simulator, so that it is possible to study easily the behaviour of the model in different scenarios. Figure 17 shows a screenshot of the defined simulator.

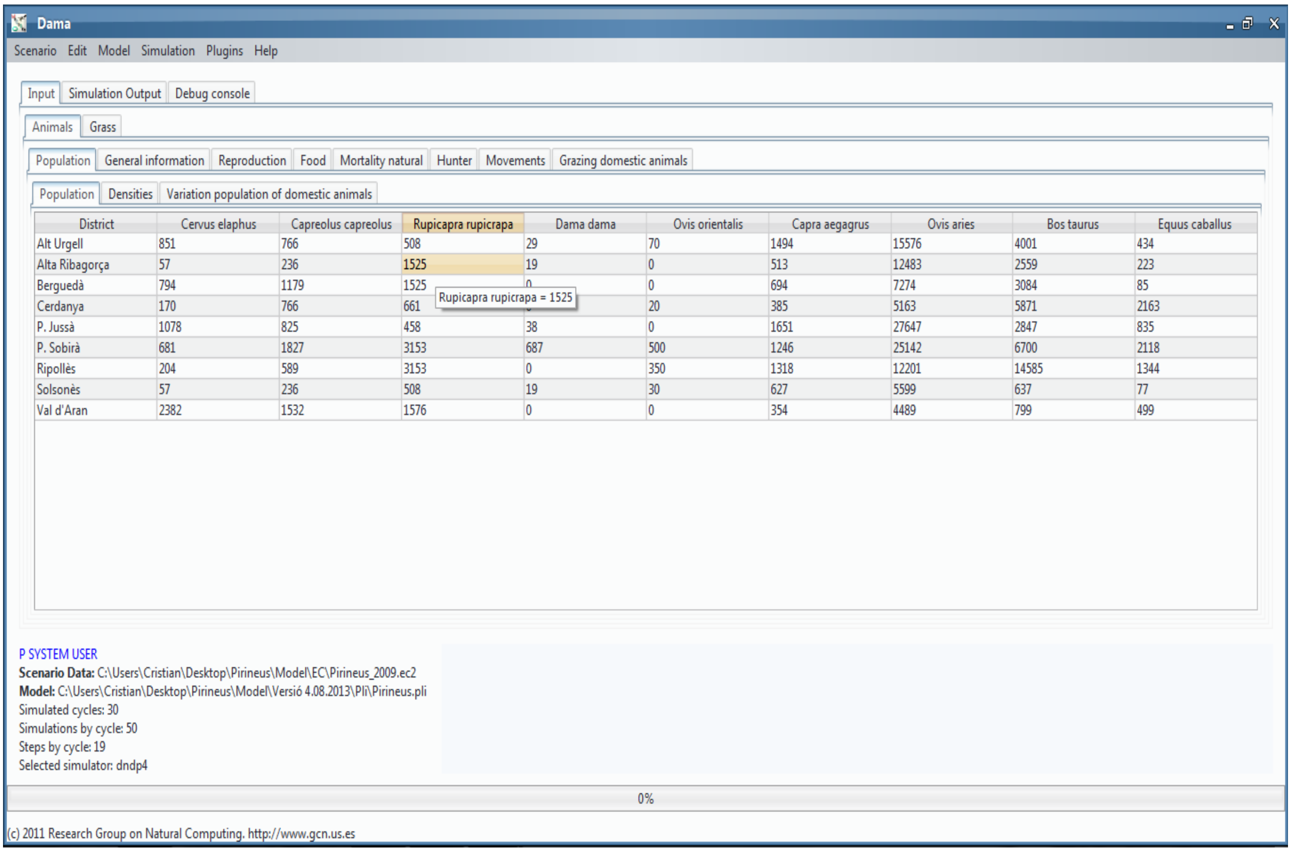


Figure 17: Screenshot of the defined simulator obtained using MeCoSim, showing the population of each ungulate species in each county in the year 2009 for the model in the Pyrenees. The user can change these values directly in the simulator in order to study different scenarios.

Chapter 5. Results for the Catalan Pyrenees

"In the pastures where there are only cattle and mares and the sheep and goats don't graze, yes, there is a greater prolifereation of pines and junipers above all." Illustrative quotation in Fernández-Giménez and Fillat (2012).

Chapter 5

Results for the Catalan Pyrenees

5.1. Application of the model

5.1.1. Field of application

First of all, it is necessary to specify the land covers that are affected by LUCC, as well as the conditions under which the model has been applied for the Catalan Pyrenees. Land-use changes or LUCC influence land covers that are pastures used for livestock farming, shrubland and forest. The meadows, despite having been included in the model, have not been taken into account in the results, as they occupy a very small part of the study area, less than 1% of the total, and do not have a significant effect on the landscape. Moreover, their evolution involves factors that were not considered in this work, determining their transformation into rangelands or into abandoned land. The remaining surface is occupied by open spaces without vegetation, located in the highest elevations, which are not affected by LUCC processes. The model considers a new land use, additional to the original covers of the Land Cover Map of Catalonia (LCMC) (CREAF, 2013), the so-called *abandoned pastures*. The aim of the inclusion of this new category was to separate grasslands used by livestock of those that were used in the past, but have been abandoned. Their grass production is, however, available for wild ungulates. The abandoned pastures, or abandoned land, are the most susceptible to evolve into shrubland and forest communities.

5.1.2. Simulated scenarios

According to possible future reforms of the Common Agricultural Policy (CAP), three scenarios have been studied in the high Catalan Pyrenees. As it is uncertain which reforms will be undertaken, the scenarios have been chosen according to the perceptions of the stakeholders involved in the management of European mountain landscapes (Bayfield et al., 2008; Renwick et al., 2013; Soliva et al., 2008) (Section 1.5., Chapter 1).

The first simulated scenario considers the continuation of the agricultural practices and trends observed between the years 2000 and 2009 without any changes in the current agricultural policy, and is therefore called *conservation of the status quo*. The second scenario modelled assumes a reduction of domestic animals grazing the mountain pastures due to a reduction of the funds intended for agriculture and farming, which is partly compensated by payments aiming at environmental issues or at the conservation of cultural landscape. Finally, the third contemplated scenario is characterized by a strong reduction of the support for agriculture and farming, without any type of compensatory aid. The basic difference in the three future scenarios is the agricultural land-use intensity produced in each case: the greater is the reduction of animals that graze the mountain pastures, the major is the abandoned surface, which is therefore susceptible to be recolonized by woody species. More information is provided in Annex B.

50 repetitions have been performed for each of the simulated scenarios in order to approximate result and real average value. All the scenarios cover a time span of 30 years, from 2009, the year of the latest land cover map, to 2039. This is a time period short enough

to make predictions, but sufficiently long to observe ecological and landscape changes (Soliva et al., 2008).

5.1.3. Goodness of fit of the model

Once the model was built, its goodness of fit was checked, *id est* is was controlled if its results fit the reality. The fact of disposing only of real data for one year has not allowed doing a validation of the model with statistical techniques. The goodness of the model has been tested by simulating the time span from 1993 to 2009 (CREAF, 2013), as real information is available for these years, conducting 50 repetitions per year. With the results obtained with the model and those observed in reality, the relative error has been calculated, which is defined as the quotient between the absolute error and the exact value. The relative error in each considered land use -forest, shrubland and grasslands- is low for the entire study area, ranging between 0% and 5% (Table 7). The grasslands include both grazing land used for livestock farming or agriculture and surfaces that have been abandoned in recent years. This is necessary because the land-use category *abandoned land* was not considered in the real data for the year 2009.

Table 7: Simulated and real surfaces for the year 2009 in the Pyrenees. The data used as a basis for the validation is from the year 1993. The relative error is provided to compare both surfaces.

Land use	Simulated (ha)	Real data (ha)	Relative error (%)
Forest	76580.67	78660	2.64
Shrubland	37752.33	37799	0.12
Grasslands (pastures + abandoned land)	75307.33	71598	5.18

5.2. Results

First of all, the LUCC results are provided for the whole of the study area and, individually, for the different Pyrenean counties. Secondly, the evolution of the landscape is shown in relation to altitude and slope ranges. Finally, the effects of slope and altitude are analysed in order to observe the LUCC distribution in accordance with the topography.

5.2.1. General results

The evolution of the surface used as pastures, grasslands (both, employed for agriculture or abandoned pastures), shrubland and forest is shown for the time span from the year 2009 to 2039 for the totality of the study area (Figure 18). The grazing intensity is inversely proportional to the abandonment of pastures and to the increase of forest surface. The reduction of shrubland obtained in the scenario 1, indicates that the ratio of transition between abandoned pastures and shrub colonization is smaller than the ratio of transition between shrub and forest. Pastures are reduced on average by 90.2% in the three simulated scenarios, being 80.15% in scenario 1, 93.13% in scenario 2 and 97.34% in scenario 3. However, when considering the whole grassland surface, this reduction is of 14.66%. Regarding the forest surface, the area covered by scrubs decreases 4.88% and forest increases 12.8%, on average. Table 8 shows the summary of relative land-use changes that have been obtained from the modelling of LUCC and the relative surface forecasted for the year 2039 for each land use and scenario.

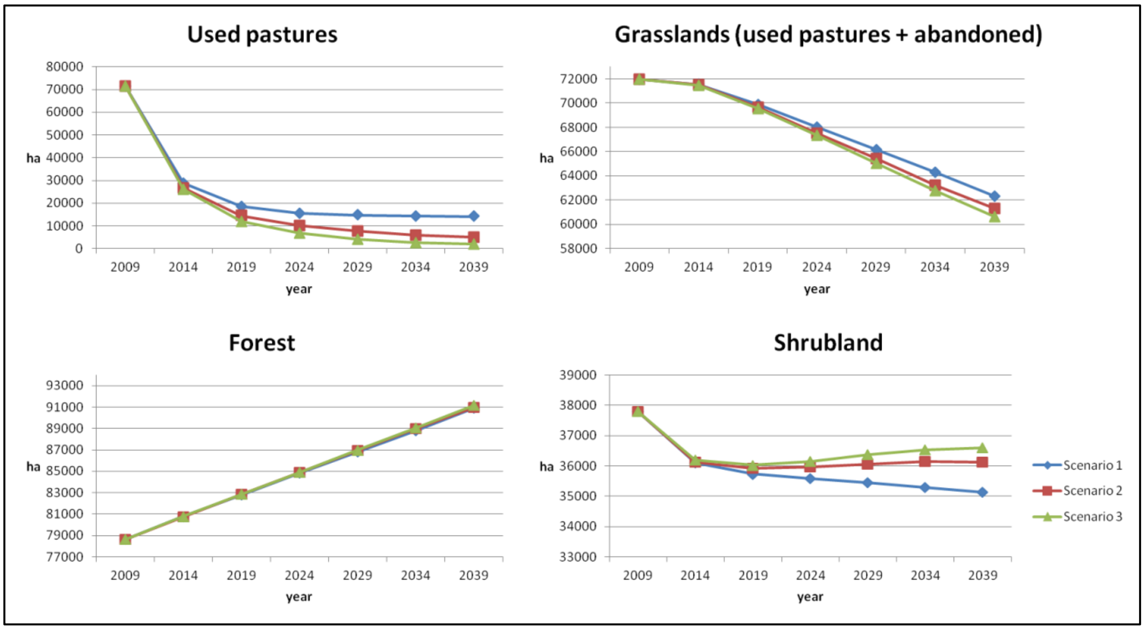


Figure 18: Evolution of the used pastures, grasslands, forest and shrubland land uses in the different simulated scenarios in the Pyrenees from 2009 to 2039.

A landscape dominated by woody vegetation, covering more than 55% of the total surface of the study area (39.85% forest and 15.74% shrubland, on average), is obtained in all three scenarios for the year 2039. Furthermore, grasslands, including used pastures and those that have been abandoned previously, are reduced as the grazing pressure decreases, although without significant differences in the three scenarios. The strong abandonment of used pastures provokes that in the year 2039 the grazing land is reduced in scenario 1 (6.22% of the total) and disappears almost completely in the scenarios 2 and 3 (2.15% and 0.83%, respectively). The surface evolution for each land use during the simulated period (2009-2039) is shown in figure 19. The absence of abandoned surface in 2009 is given, as already mentioned above, due to the non-existence of this category in the land cover map of the year 2009 (CREAF, 2013), which was used as a modelling basis.

Table 8: LUCC modelled in the Pyrenees for the time span from 2009 to 2039 and relative surface of all land uses modelled for the year 2039. 1 Grasslands, including used and abandoned pastures. 2 Land uses not included in LUCC study. Individual data on abandoned land is not included.

Land use	2009 - 2039 (%)			2039 surface (%)		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Forest	15.57	15.66	15.87	39.8	39.83	39.91
Shrubland	-7.04	-4.41	-3.2	15.38	15.82	16.02
Used pastures	-80.15	-93.13	-97.34	6.22	2.15	0.83
Grasslands[1]	-13.38	-14.85	-15.75	27.3	26.83	26.55
Agricultural areas[2]	0	-2.76	-27.49	0.16	0.16	0.12
Open spaces[2]	0	0	0	17.52	17.52	17.52

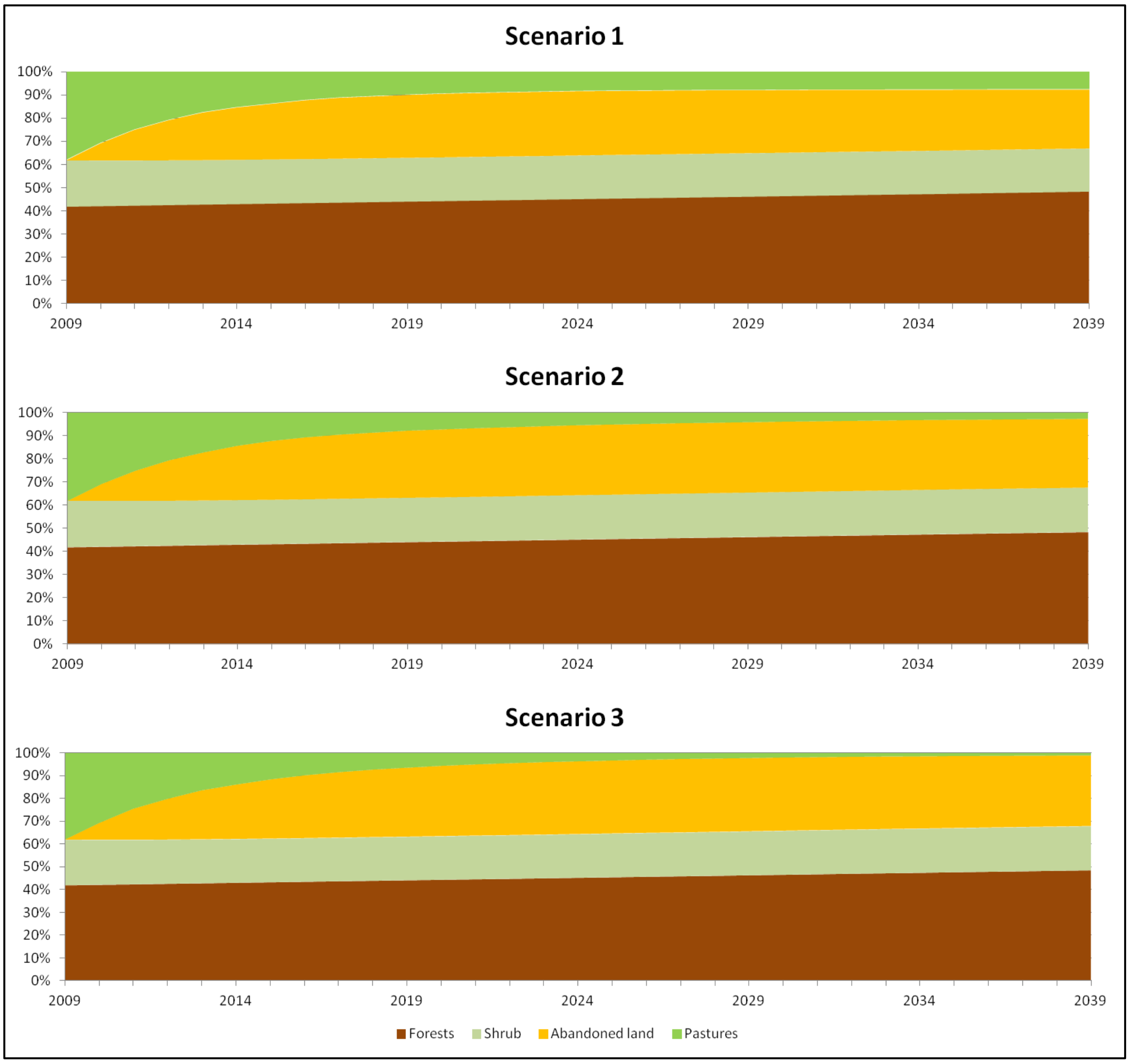


Figure 19: Evolution of the surface occupied by each land use from 2009 to 2039 in the Pyrenees.

5.2.2. Results per counties

The results are broken down per administrative unit (County) (Figure 20). These show that all regions suffer an important loss of grazing land. Val d'Aran is the county with the highest percental loss in all scenarios, 97.87% on average, and with the least relative surface of pastures in comparison with the whole study area of the county in the year 2039, 0.87% on average. Cerdanya is the county that suffers the least pasture reduction in the simulated scenario 1 (61.33%) and Solsonès in scenarios 2 and 3 (81.82% and 89.83%, respectively). With regard to the relative surface of used pastures at the end of the simulated period, in the year 2039, Ripollès maintains the greatest surface in all scenarios, 15.43% in the first, 6.16% in the second and 2.12% in the third. The surface occupied by shrubland is reduced in almost all counties, except in Val d'Aran, Alta Ribagorça and Ripollès, where the overall average considering all three scenarios increases 2.29%, 5.81%, and 12.31%, respectively in each county. For the year 2039, the Western counties -Alta Ribagorça, Val d 'Arán, Pallars Jussà and Pallars Sobirà- and Ripollès are expected to contain the highest proportion of shrubland surface (16.86% on average, compared to 9.55% in the other counties). Finally, the counties of the Western Pyrenees and Ripollès, especially Pallars Jussà and Val d'Aran, experience the highest relative increase of forest surface (36.85% and 40.18% on average, respectively). At the same time, these counties are - together with Alta Ribagorça - the ones with the lowest relative area occupied by forest in 2039, 17.75% in Pallars Jussà, 26.38% in Alta Ribagorça and 27.10% in Val d'Aran.

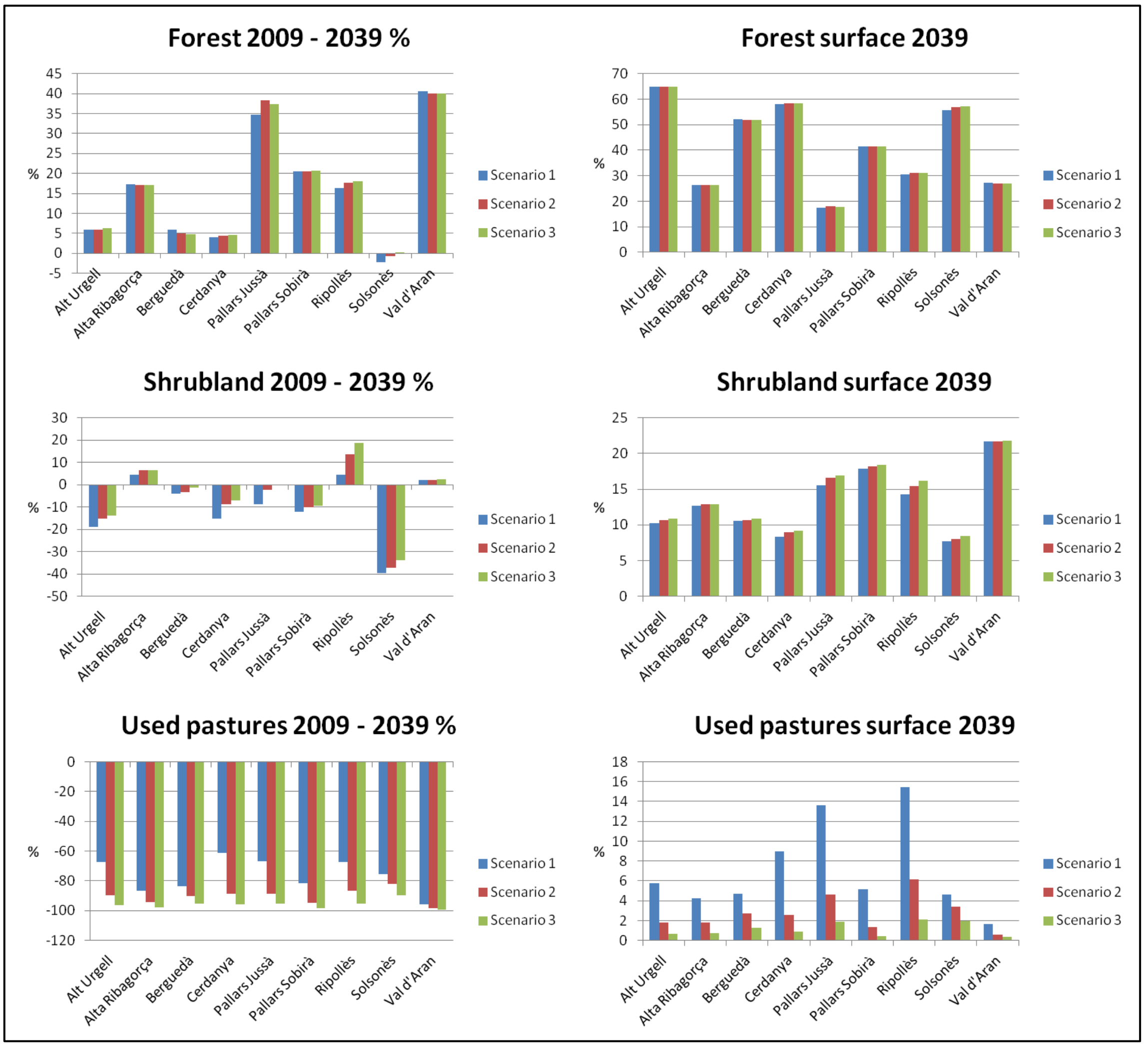


Figure 20: Relative changes in land-use surface simulated from 2009 to 2039 for each Catalan county and relative surface in the year 2039, calculated regarding the total study area surface in each county.

5.2.3. Results for altitude and slope ranges

Having presented the general results for the whole study area and for the different counties, the results regarding slope and altitude are displayed for the total study area, first separately for each condition and afterwards in their combination.

Regarding the slope, two different ranges were differentiated: areas with gentle and moderate slopes (≤30°) and with steep slopes (>30°). The results show that in scenario 1, at the end of the studied period, more grazing land is lost on steep slopes (85.16%) than on gentle slopes (79.18%). In contrast, in the second and the third scenario, the loss is higher in the gentle slope range (93.31% and 97.74% respectively) than on steeper slopes (92.19% and 95.27%). The surface covered by shrubby vegetation is reduced on average by 21.48% on steep slopes, whereas in areas with gentle slopes it increases 2.29% on average. The forest surface grows in a similar way in all scenarios for each slope range, with an average increase of 18.81% on steep slopes and of 14.89% on gentle slopes. Table 9 shows the LUCC related to each land use and figure 21 provides the proportion of surface occupied by each land-use considered in the year 2009 and the resulting proportions for each simulated scenario in the year 2039.

Table 9: Relative changes in each land use and in each scenario for the Pyrenees in the time span 2009-2039, separated by slope range.

Land use	Slope range	Scenario 1 (%)	Scenario 2 (%)	Scenario 3 (%)
Forest	≤30°	14.73	14.87	15.06
	>30°	18.8	18.66	18.97
Shrubland	≤30°	-0.57	2.96	4.49
	>30°	-22.02	-21.45	-20.96
Used pastures	≤30°	-79.18	-93.31	-97.74
	>30°	-85.16	-92.19	-95.27

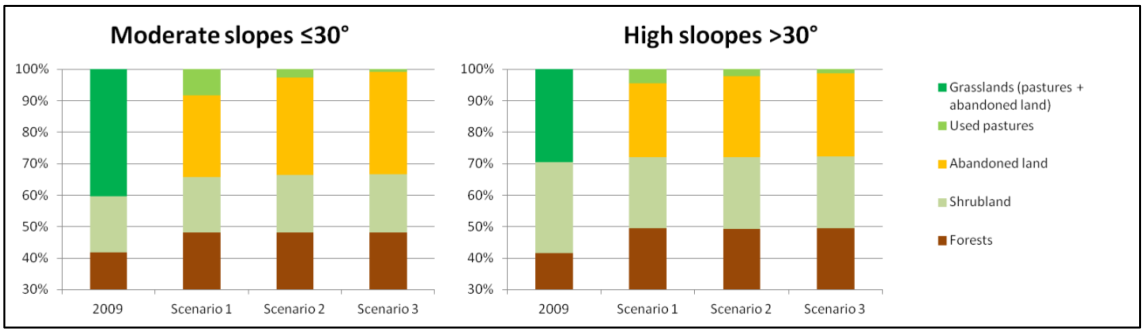


Figure 21: Pyrenees' land-use surfaces of the years 2009 and 2039 for each simulated scenario and separated by slope ranges.

The results have been differentiated by three altitudinal ranges: 1700-2200 m, 2200-2600 m and above 2600 m (above the tree line). These results show that the used pastures decrease on average 93.71% in the first altitudinal range and 90.87% in the second, while this reduction is less intense in the third range, 53.12% on average. The biggest differences between the simulated scenarios were observed for the third altitudinal range, obtaining a loss of pastures of 17.64% in the first scenario, of 56.67% in the second and of 85.05% in the third. With regard to the shrubby vegetation, the surface decreases on average 14.37% in the first altitudinal range, while it increases 32.61% in the second range. Finally, the surface covered by forest increases 13.37% in the first altitudinal range, and more intensely, 44.66%, in the second one. The surface occupied by woody vegetation in the third altitudinal range is not significant, as it is located above the tree line. These relative surface variations of each land use, separately by altitudes, are displayed in table 10. Moreover, figure 22 provides the relative surfaces forecasted for each land use and each scenario in the year 2039, as well as the existing surface at the beginning of the modelling (2009).

Table 10: Relative changes in each land use and in each scenario for the Pyrenees in the time span 2009-2039, separated by altitudinal range.

Land use	Altitude range	Scenario 1 (%)	Scenario 2 (%)	Scenario 3 (%)
Forest	1700 - 2200 m	13.28	13.33	13.49
	2200 - 2600 m	44.02	44.53	45.43
	>2600 m	0	0	0
Shrubland	1700 - 2200 m	-15.48	-14.13	-13.5
	2200 - 2600 m	26.28	33.99	37.55
	>2600 m	0	0	0
Used pastures	1700 - 2200 m	-86.77	-96.08	-98.27
	2200 - 2600 m	-86.51	-94.29	-97.8
	>2600 m	-17.64	-56.67	-85.05

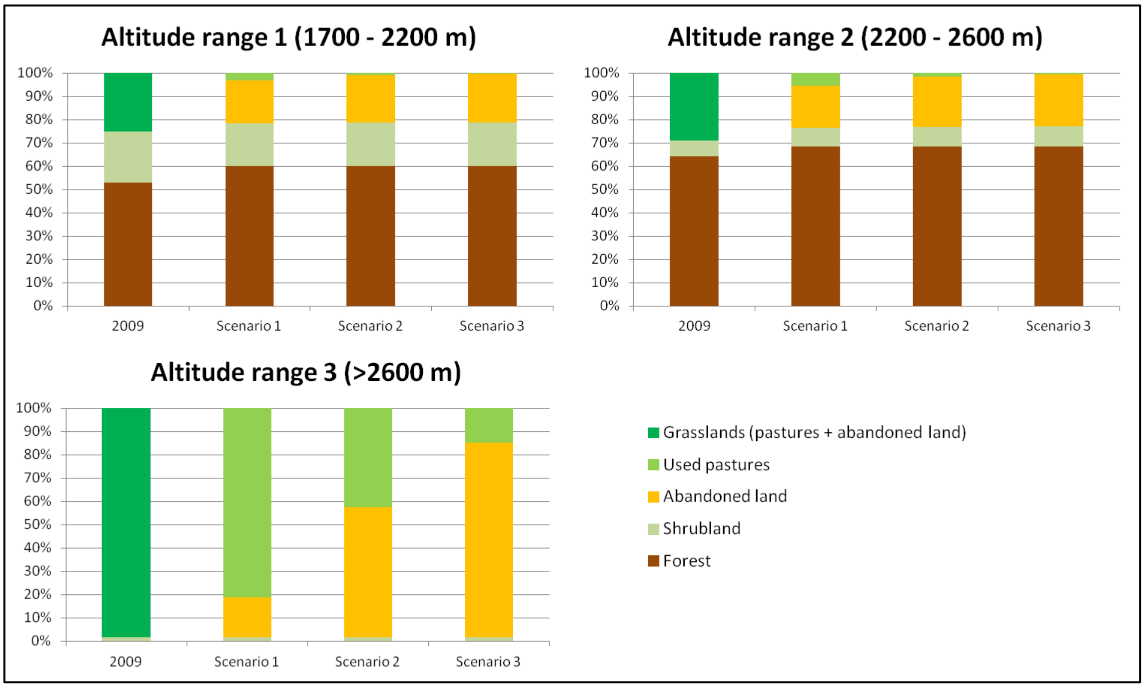


Figure 22: Pyrenees' land-use surfaces of the years 2009 and 2039 for each simulated scenario, separated by altitudinal ranges.

Once the results were presented separately regarding different slopes and altitudinal ranges, both effects are combined for each simulated scenario and for each land use, used pastures, shrubland and forest. First of all, LUCC are studied in pastures with livestock use (Figure 23). The results show a relative reduction in all slope and altitude combinations. The largest relative reduction of pastures occurs in the third studied scenario, in concrete in the combination of the first altitudinal range with gentle slopes, with a loss of 98.74% compared to the year 2009. However, no important differences exist between the first and the second altitudinal range. Furthermore, the combination with the least loss, 6.53%, is given in the first scenario, in the third altitudinal range and on gentle slopes. When analysing LUCC in terms of absolute abandoned surface, the combinations of first and second altitudinal ranges with gentle slopes (≤30°) present the biggest increases with an average of 28,360 ha and of 24,234 ha, respectively.

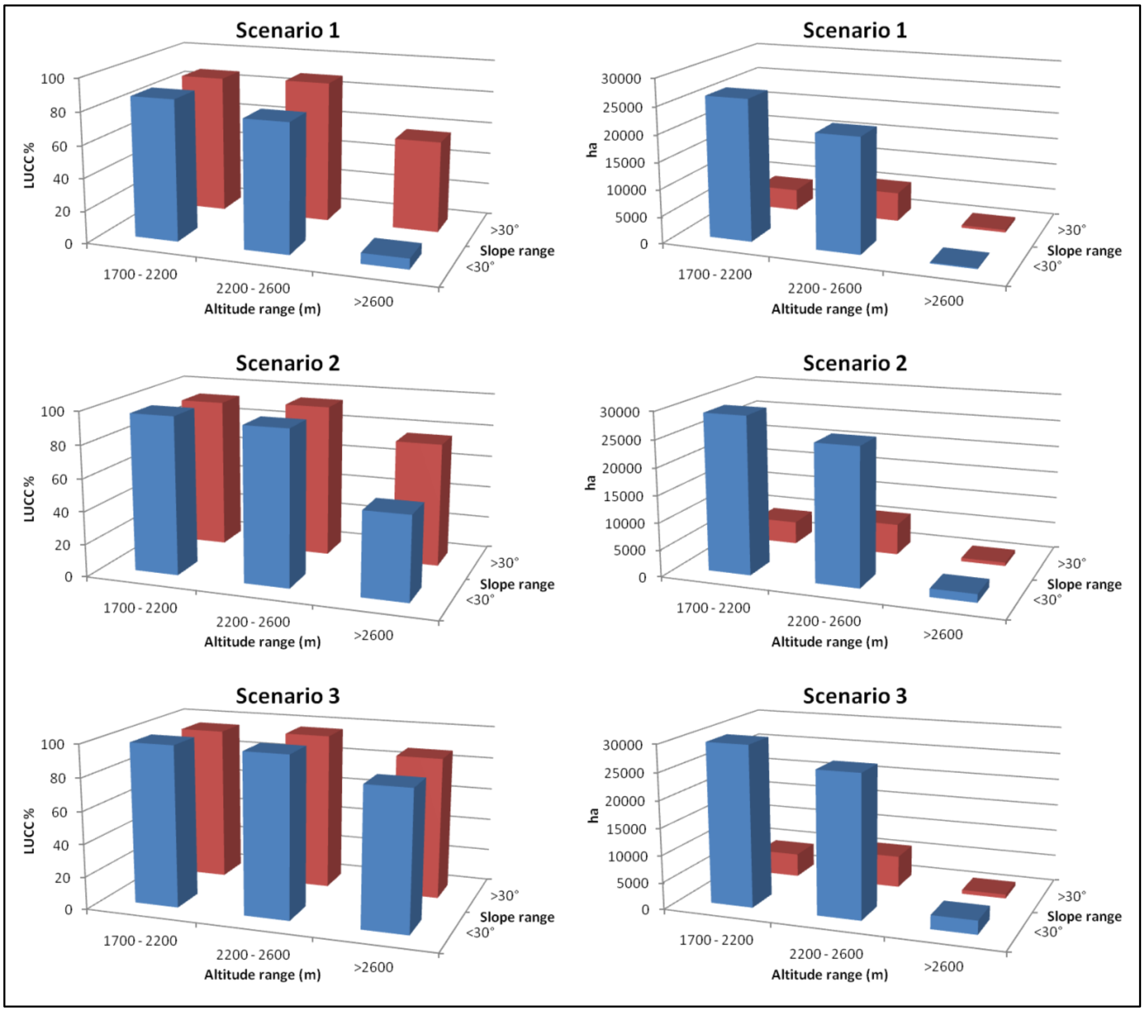


Figure 23: Used pastures surface reduction in the Pyrenees separated by altitudinal range and slope for each scenario in the simulated period 2009-2039.

The situation is slightly more complex regarding shrubs, since this category includes abandoned land encroached by shrubs, shrubland evolving into forest and shrubland turned into pastures due to fire. The results show a very similar trend in all simulated scenarios, albeit with different intensities (Figure 24). Shrubland decreases at the first altitudinal range and increases at the second. The maximum realtive surface reduction is given in the first altitudinal range for steep slopes, being 27.72% on average for the three scenarios, representing, hence, a reduction of 2607.92 ha on average. By contrast, the maximum increase is given on moderate slopes at the second altitudinal range, representing on average 41.24% or 2324.67 ha.

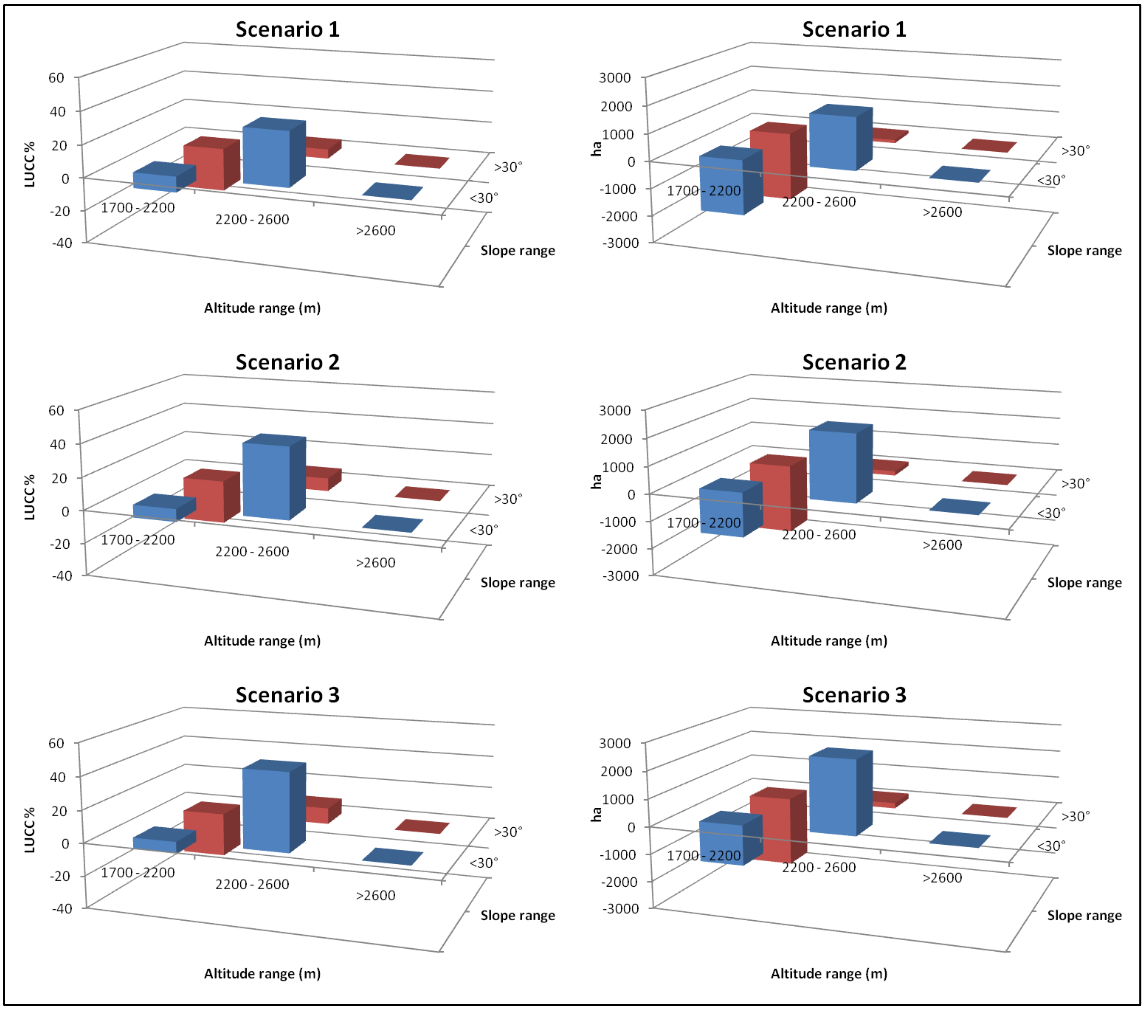


Figure 24: Shrubland surface changes in the Pyrenees, separated by altitudinal range and slope for each scenario in the simulated period 2009-2039.

Finally, the LUCC show again an almost identical behaviour in all three scenarios with regard to forest (Figure 25). The largest relative increase in forest surface occurs in the intermediate altitudinal range (2200-2600 m), more intensely in the combination with moderate slopes, 50.19% on average, than on steeper slopes, 29.56% on average. However, the absolute reforested surface is the most important in the combination of low slopes with the first altitudinal range, where this increase is translated into an average of 7113.67 ha of new forest (7063 ha in the first simulated scenario, 7102.5 ha in the second and 7175.5 ha in the third).

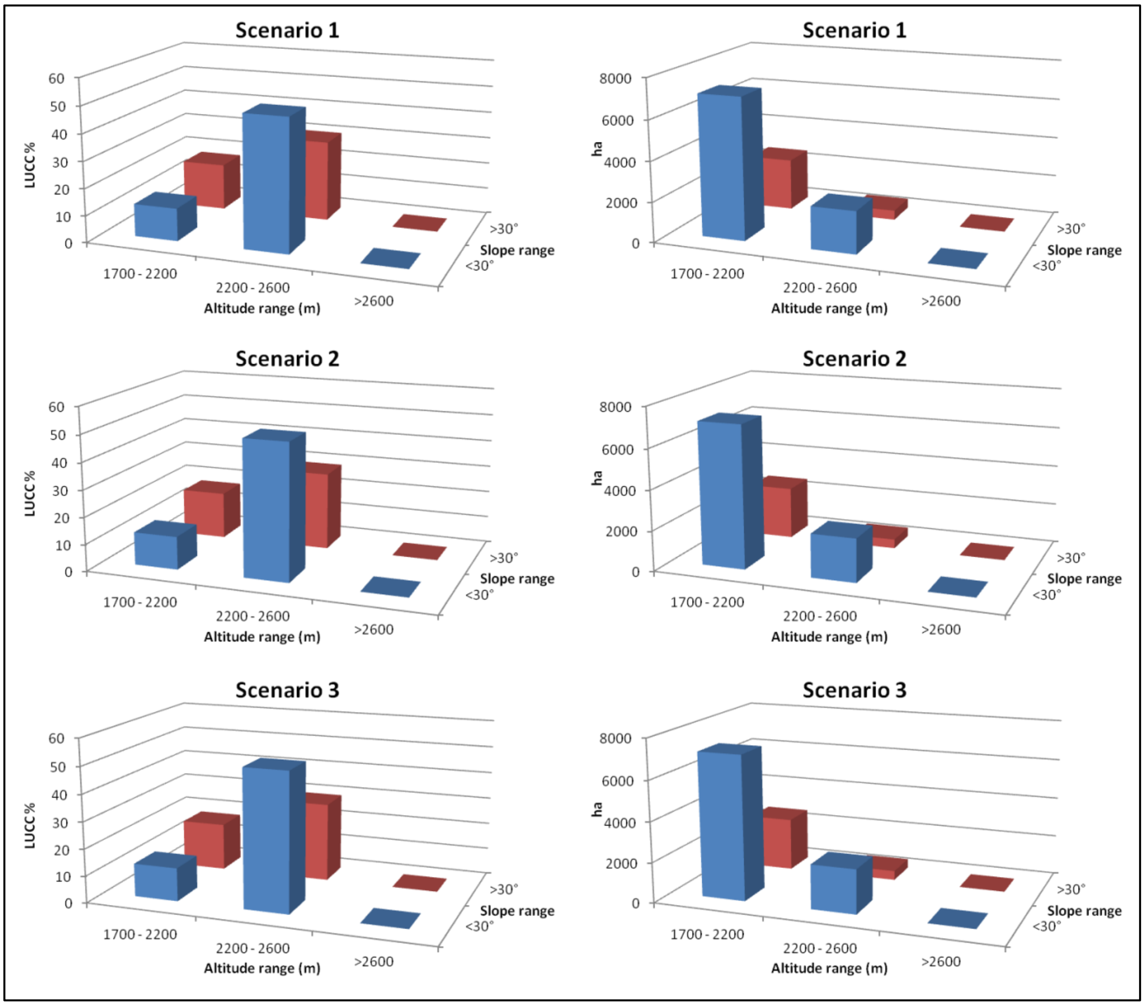


Figure 25: Forest surface change in the Pyrenees separated by altitudinal range and slope for each scenario in the simulated period 2009-2039.

Chapter 6. Results for the Stubai Valley

"The relatively low importance of agriculture in the Stubai Valley is also reflected in the development of livestock units. After reaching a peak in the mid-20th century, these [the livestock units] fell in all municipalities." (Tasser et al., 2012c)

Chapter 6

Results for the Stubai Valley

6.1. Application of the model

6.1.1. Field of application

First of all, definitions of the land uses for which the LUCC processes have been modelled are given and some of the conditions under which the model has been applied in the Stubai Valley are displayed. In this second study area, the land-use covers affected by changes in land use are moderately intensive used grasslands, extensively used grasslands, abandoned agricultural surface and forest. Intensively used grasslands located at the valley bottom have been incorporated into the model but have not been taken into account in LUCC modelling, since the surface of this land use is of minor importance and is not affected by the landscape changes treated in this work: land abandonment and spontaneous reforestation (Section 1.2.2., Chapter 1). In the study area exist, in addition, agriculturally non-usable areas located in the highest and least accessible zones. However, these surfaces produce grass that can be grazed by wild ungulates inhabiting the valley.

In all scenarios, the model has been applied for a period of 30 years, from 2003, the year of the latest land-use map, to 2033, with 50 replications per year. This period was selected because it is a sufficiently short term to make assumptions over future agricultural development and sufficiently long to reveal possible ecological and landscape changes (Soliva et al., 2008).

6.1.2. Simulated scenarios

Land-use and cover changes (LUCC) in the Stubai Valley have been modelled for the same future scenarios considered in chapter 5 section 5.1.2, which were chosen according to the future previsions of experts and stakeholders, based on hypothetical changes in the European Common Agricultural Policy (CAP) (Section 1.5., Chapter 1). In the first scenario, *status quo*, the continuation of current land-use intensity observed between 2000 and 2010 is simulated, expecting no changes in agricultural policy. The second scenario assumes a reduction in agricultural funding, partly compensated with environmental or cultural aids. Such compensations are not presumed in the third studied scenario, anticipating, hence, a strong decrease of all economic support for the sector. The anticipation of more or less future funding is translated into trends regarding the livestock stoking rate throughout the modelling period: a continuation of the current slight decrease in the first, a significant reduction in the second, and a strong decline in the third scenario. More information is provided in Annex B.

6.1.3. Goodness of fit of the model

In order to verify that the model conforms to reality, the results of a simulation of 30 years from 1973 to 2003 have been compared with the actual data for the years 1988 and 2003, obtained from Tappeiner et al. (2008). The criterion of the relative error has been used to perform the comparison, which is defined as the quotient between the absolute error and the exact value. The calculated relative error is less than 10% for the two years for which the surfaces have been compared, as can be seen in table 11.

Table 11: Simulated and real surfaces for the years 1988 and 2003. The data used as a base for the validation are from the year 1973 (Tappeiner et al. 2008). To compare both surfaces the relative error is provided.

Cultural land used	Simulated (ha)	Real data (ha)	Relative error (%)	Simulated (ha)	Real data (ha)	Relative error (%)
			1988			2003
Forest	6852	7143	4.07	6951	7263	4.30
Abandoned land	4258	4065	4.75	4273	3951	8.15
Moderately intensive used grassland	316	332	4.82	299	280	6.79
Extensively used grassland	939	939	0.00	842	890	5.39

6.2. Results

Firstly, the general results regarding the Stubai Valley are presented, and, secondly, analyzed differentiated by slope and altitudinal range for each considered land use.

6.2.1. General results

In general terms, abandonment continues on subalpine pastures during the simulated time span (2003-2033), whereat moderately and extensively used grasslands are decreasing. As a consequence, forest surface increases in all scenarios (Figure 26). As expected, the reduction of agricultural surface is proportional to the agricultural intensity, reaching its maximum in the third simulated scenario. In moderately intensive used grasslands occurs a surface reduction of 6.07% in scenario 1, 43.21% in scenario 2 and 69.64% in scenario 3 (39.64% on average). For extensively used grasslands this reduction is more pronounced, with relative values of 24.04% in the first, 63.6% in the second and 80.67% in the third scenario (56.1% on average). The abandoned land increases for the three scenarios 11.3% on average. Moreover, forest vegetation increases parallel to the decrease of grasslands, 2.14% on average in all scenarios (Table 12).

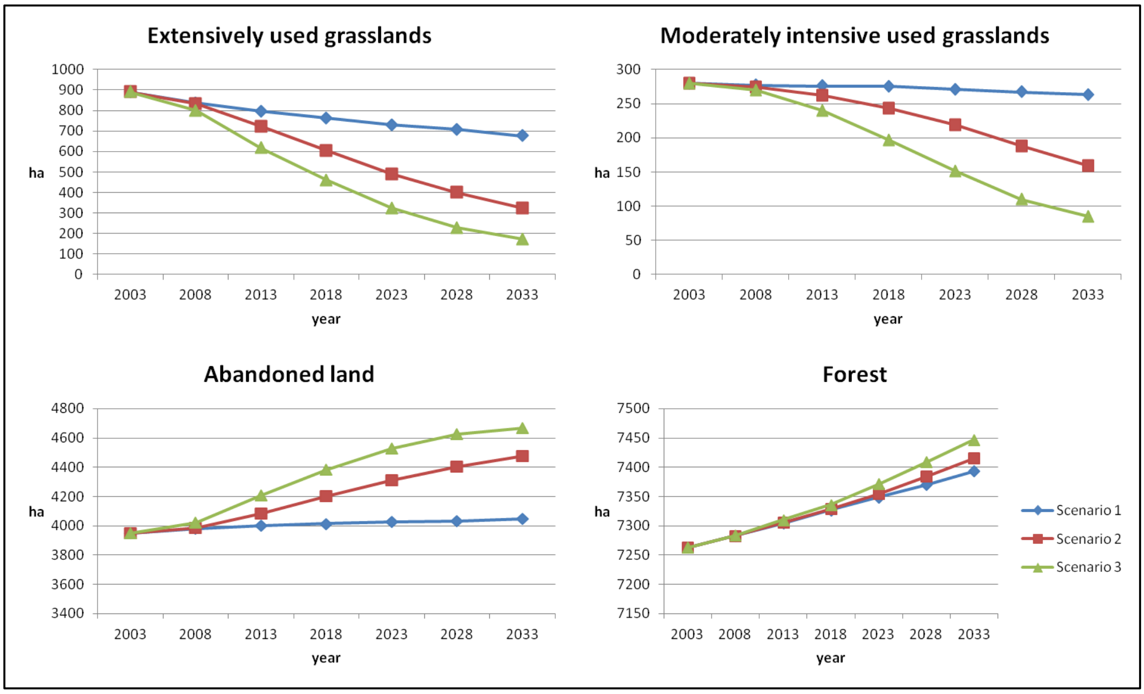


Figure 26: Evolution of the cultural land uses in the Stubai Valley from 2003 to 2033 in different simulated scenarios.

The landscape forecasted for the year 2033 in scenario 1 is characterized by being composed of an extent forest area (49.92% of the total study area) and of abandoned agricultural land (27.33%). Furthermore, the surface occupied by meadows and pastures has decreased slightly compared to the situation in the year 2003. The meadow and pasture surfaces, which include moderately and extensively used grasslands, represent in this first scenario 6.34% of the total simulated area for the year 2033. In scenario 2, the resulting landscape in the year 2033 is dominated by forest (50.08%) and by abandoned land (30.24%) and the used grasslands have decreased significantly, representing only 3.26% of the total surface. Finally, in the third simulated scenario, forest represents 50.3% of the whole area and abandoned land 31.54%. In this third scenario the agricultural surface reduction is much more important than in the preceding scenario, representing only 1.73% of the surface, which means that agricultural surfaces will have almost completely disappeared. Table 2 provides the relative land-use variations obtained by means of the simulation of the period from 2003 to 2033 and the surface occupied at the end of this time span. Figure 27 complements these results with the graphic evolution of land-use surfaces over time.

Table 12: LUCC modelled in the Stubai Valley for the time span from 2003 to 2033 and relative surfaces of all modelled land uses for the year 2033. 1 Not included in LUCC processes.

Land use	2003 - 2033 LUCC (%)			2033 Surface (%)		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Forest	1.79	2.09	2.53	49.92	50.08	50.3
Abandoned land	2.43	13.31	18.17	27.33	30.24	31.54
Agriculturally non-usable area[1]	0	0	0	9.76	9.76	9.76
Intensively used grasslands[1]	0	0	0	6.66	6.66	6.66
Moderately intensive used grassland	-6.07	-43.21	-69.64	1.78	1.07	0.57
Extensively used grassland	-24.04	-63.6	-80.67	4.56	2.19	1.16

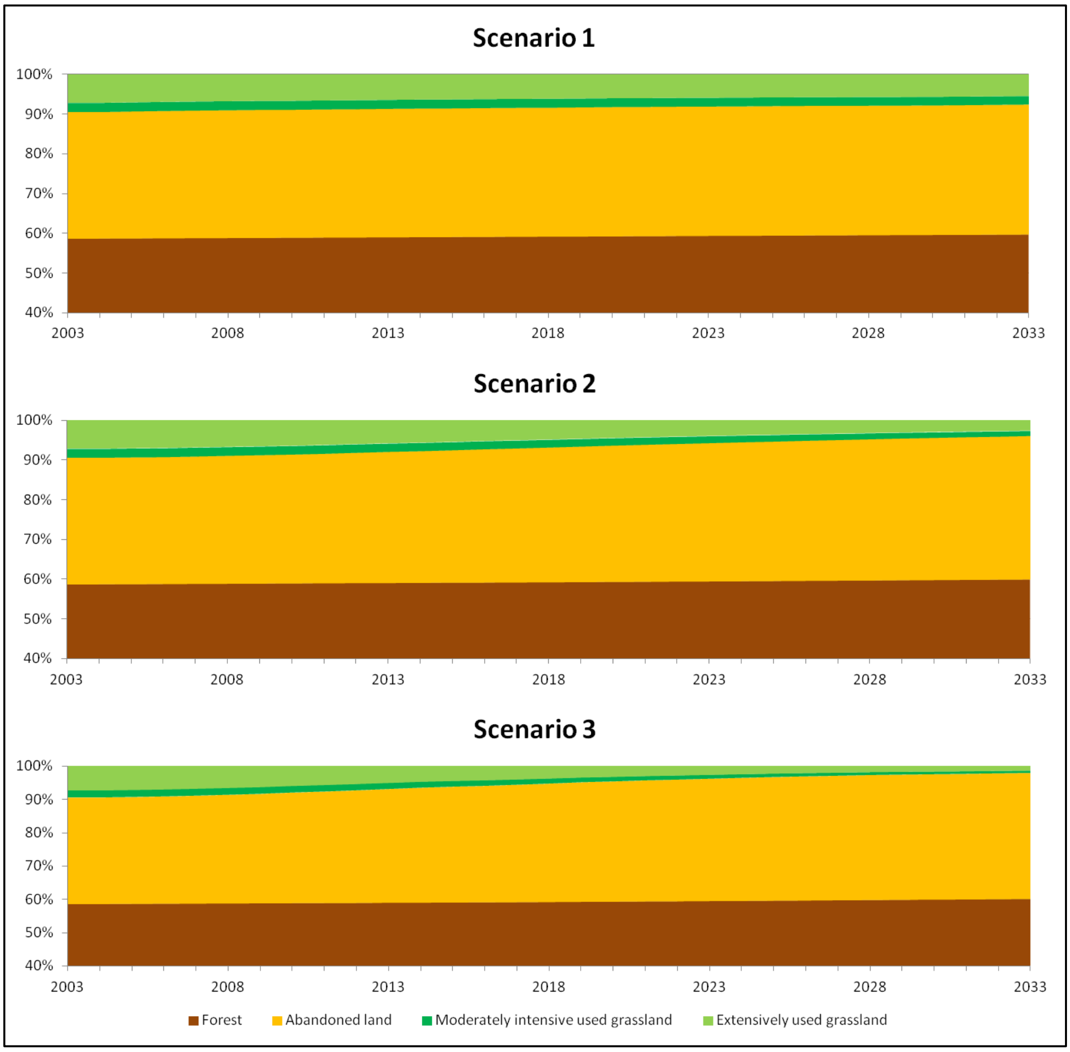


Figure 27: Evolution of the surfaces occupied by each land use from 2003 to 2033 in each simulated scenarios.

6.2.2. Results differentiated by altitudinal ranges and slope

Land-use and cover changes do not occur homogeneously throughout the study area, instead their effects vary depending on altitude and slope. First of all, LUCC are evaluated differentiating the slopes according to their accessibility for different livestock types: low slopes, including moderate and gentle slopes of less than (or equal to) 30°, accessible for all types of livestock and steep slopes greater than 30°, not accessible for cattle and horses. On the one hand, the maximum agricultural surface reduction corresponds to extensively used grasslands on steep slopes, with percentages of 48.18%, 78.13% and 85.68%, respectively in the different studied scenarios. On the other hand, the minor loss of agricultural surface occurs to moderately intensive grasslands on high slopes, with no reduction in scenario 1, 19.05% in scenario 2 and 42.86% in scenario 3. Moderately intensive used grasslands decrease on average 41.18% on low slopes and 20.64% on high slopes, while extensively used grasslands are reduced by 45.05% on low slopes and 70.66% on high slopes. The abandoned land increases on average 21.31% on low slopes and 6.53% on steep slopes. Finally, forest undergoes a relative increase of 3.02% on gentle slopes and 1.82% in the range of steep slopes (Table 13). Figure 28 provides the relative surface obtained for each land use and in each scenario for the year 2033, as well as the observed relative surface in 2003.

Table 13: Relative changes (LUCC) obtained for the time span 2003-2033 for each simulated scenario and land use separated by slope range.

Land use	Slope range	Scenario 1 (%)	Scenario 2 (%)	Scenario 3 (%)
Forest	≤30°	2.01	2.88	4.17
	>30°	1.71	1.8	1.94
Abandoned land	≤30°	0.31	25.31	38.32
	>30°	3.44	7.59	8.56
Moderately intensive used grassland	≤30°	-6.56	-45.17	-71.81
	>30°	0	-19.05	-42.86
Extensively used grassland	≤30°	-5.73	-52.57	-76.88
	>30°	-48.18	-78.13	-85.68

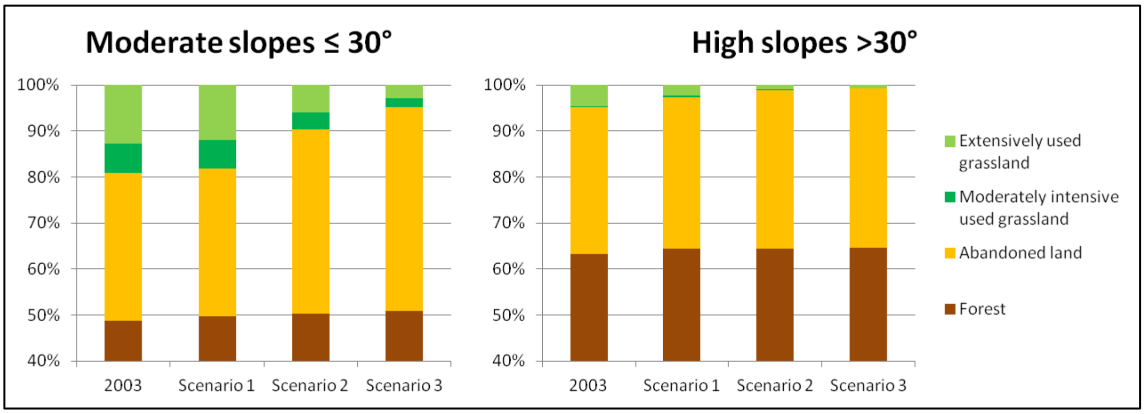


Figure 28:Land-use surfaces in the Stubai Valley observed in 2003 and forecasted for 2033, displaying the different simulated scenarios separated by slope ranges.

In a second step, the same procedure has been performed regarding altitudinal ranges. The considered altitudinal ranges are the following four: the first and lowest range, from 886 to 1500 m; the second, from 1500 to the upper limit of the forest, located at 2150 m; the third from 2150 m to 2600 m and the fourth, the highest, which covers the entire surface above 2600 m. In table 14 the relative land-use surface changes can be seen. Furthermore, figure 29 shows the percentage of relative surface obtained at the end of the simulation period for each land use and scenario. Moderately used grasslands decrease in the first (24.32% on average) and in the second altitudinal range (45.15%), while the extensive pastures decrease mainly in the second (63.98%) and third (25.82%) altitudinal range. In both land uses the most important relative surface reduction occurs in the second range (1500-2150 m). These differences are given due to the altitudinal stratification of alpine pastures, since moderately grasslands are found in the first and second range, while extensive grasslands exist mainly in the second and third range. The abandoned land increases in the ranges in which meadows and pastures decrease (first, second and third altitudinal range), but most pronouncedly in the first altitudinal range in the scenarios 2 and 3, where abandoned surface increases more than 100%. Finally, forest vegetation increases especially in the second altitudinal range, with an average of 3.21% in the three scenarios. In the fourth altitudinal range no landscape changes have been obtained, because the whole area consists of formerly abandoned pastures and agriculturally non-usable area that are not encroached by woody vegetation as they exceed the potential alpine tree line (>2150 m).

Table 14: Relative changes (LUCC) obtained for the time span 2003-2033 for each simulated scenario and land use separated by altitudinal range.

Land use	Altitude range	Scenario 1	Scenario 2	Scenario 3
Forest	886 - 1500 m	0.04	0.33	0.95
	1500 - 2150 m	2.88	3.2	3.54
	2150 - 2600	1.9	1.9	1.9
	>2600 m	0	0	0
Abandoned land	886 - 1500 m	-33.33	200	533.33
	1500 - 2150 m	6.11	30.37	39.2
	2150 - 2600	-0.09	1.21	2.9
	>2600 m	0	0	0
Moderately intensive used grasslands	886 - 1500 m	0	-20.27	-52.7
	1500 - 2150 m	-8.25	-51.46	-75.73
	2150 - 2600	0	0	0
	>2600 m	0	0	0
Extensively used grasslands	886 - 1500 m	0	-10	-23.33
	1500 - 2150 m	-29.39	-73.68	-88.86
	2150 - 2600	-2.11	-23.94	-51.41
	>2600 m	0	0	0

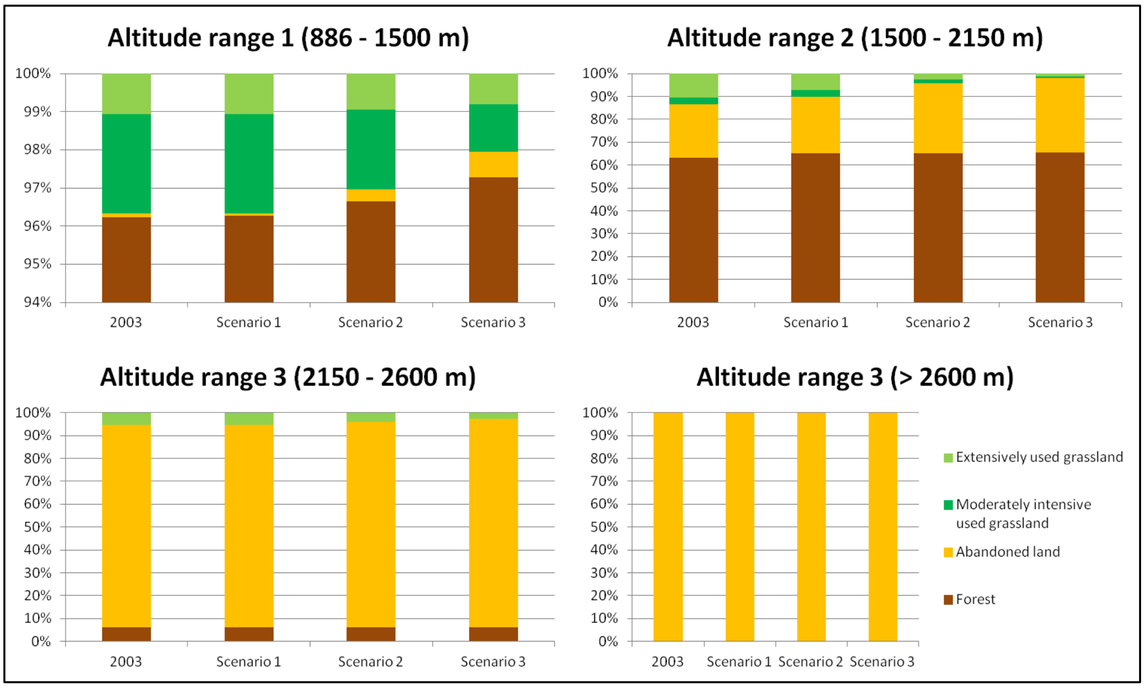


Figure 29: Land-use surfaces observed in the Stubai Valley in 2003 and forecasted for the year 2033 for the different simulated scenarios differentiated by altitudinal ranges.

Finally, the land-use changes obtained separately for slope and altitudinal ranges are presented together, combining both dimensions regarding moderately intensive and extensively used grasslands and forest surface. These results show that in considering the two agricultural land uses together, including moderately and extensively used grasslands, the most likely zones to be abandoned are those located on steep slopes (>30°) and in the second altitudinal range (1500-2150 m). In this combination of slope and altitudinal range, meadows and pastures reduce 57.05% in the first, 84.33% in the second and 90.28% in the third scenario

(77.22% on average). This phenomenon is especially clear in scenario 1, where the reduction is less than 10% in any other combination of slope and altitude. To the extent that the agricultural intensity is reduced in the scenarios 2 and 3, the abandoned surface located on moderate and gentle slopes increases progressively. When, instead of the relative surface reduction, the absolute surface variation (ha) is taken into account, the situation is different. The second altitudinal range (1500-2150 m) is still the one in which more agricultural surface is lost and in scenario 1 the greatest loss continues to occur on steep slopes (>30°), with a reduction of 182 ha. However, in the scenarios 2 and 3, the highest decrease is predicted for the moderate and gentle slope range (≤30°), with an absolute reduction of 366 ha and 506 ha, respectively (Figure 30).

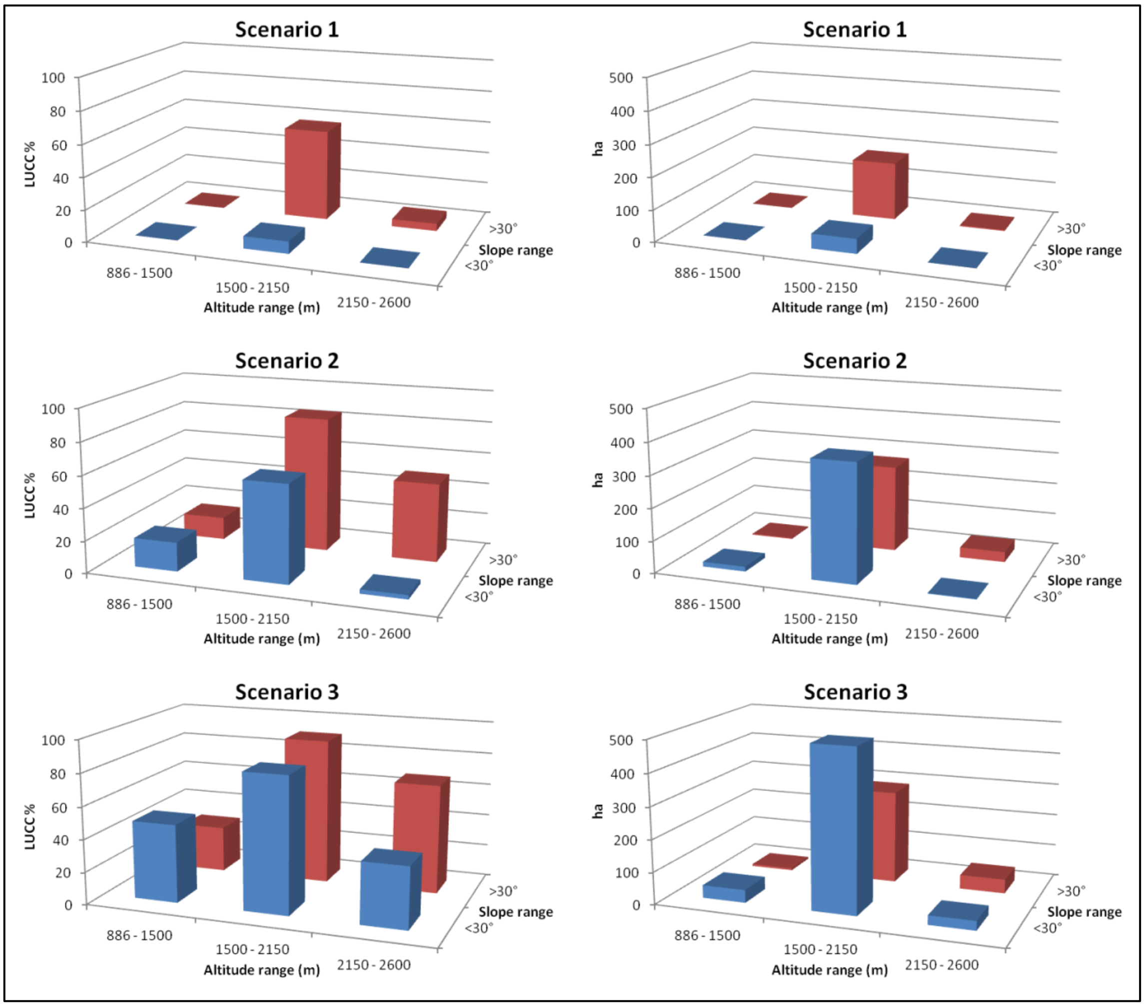


Figure 30: Reduced surface and percentage of reduction of agricultural used grasslands separated by altitudinal and slope range for each simulated scenario from 2003 to 2033. Moderately and extensively used grasslands have been grouped in the first and second slope range, but in the third only extensive grasslands are included, because moderately intensive used grasslands do not appear in this range.

Figure 31 displays the distribution of agricultural surface reduction, separately for both agricultural land uses. Regarding moderately intensive used grasslands, the biggest relative reduction is found for the second altitudinal range (1500-2150 m) on gentle and moderate slopes (≤30°), with a surface reduction of 8.99% in scenario 1, 53.97% in scenario 2 and 77.77% in scenario 3. This situation is especially explicit in the first scenario, as no surface reductions are forecasted for any other slope and altitude combinations. Grassland surface reduction in first altitudinal range (886-1500 m) is only expected for low slopes in the second (21.42%) and the third scenario (55.71%). This land use does not exist in the third altitudinal range. With regard to extensively used grasslands, reductions are generally stronger than in moderately intensive used grasslands. Similarly, the maximum percentage of grassland decrease occurs in the second altitudinal range on the steeper slopes (>30°), where a reduction of 60.26%, 87.75% and 92.38%, respectively in the scenarios 1, 2 and 3, is expected. Moreover, the least reduction regarding extensive grasslands occurs in the combination of low slopes with the first altitudinal range, with a agricultural surface decline of 7.69% in the third simulated scenario, remaining unchanged in the others (Figure 31).

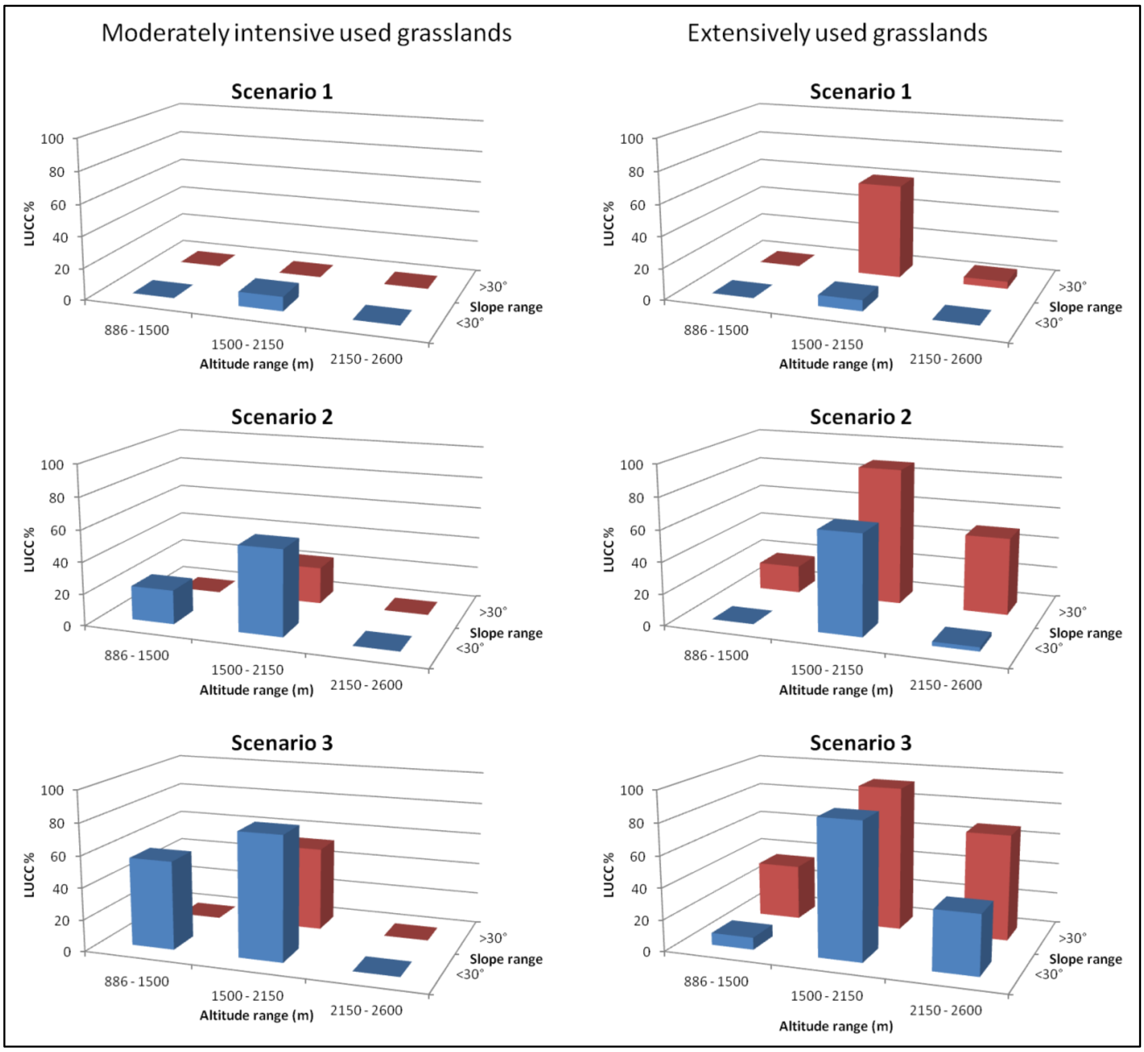


Figure 31: Relative surface reduction of moderately (left) and extensively used grasslands (right) for each simulated scenario between 2003 and 2033.

Finally, the results for forest expansion are presented, combining the effects of altitude and slope. The highest relative increase of the forest surface occurs in all simulated scenarios in the second altitudinal range (1500-2150 m) and on gentle and moderate slope ranges (≤30°), with a forest expansion of 3.94% in the first scenario, 4.98% in the second and 6.01% in the third. Moreover, the least intensive surface growths are forecasted for the first altitudinal range, exceeding only for low slopes in the third scenario 1% (2.32%). In the case of the new total absolute reforested area, this is located mainly in the second altitudinal range. Within this altitudinal range and on the high slope (>30°), the forest increase results in 88 new hectares in the first, 92 hectares in the second and 97 hectares in the third scenario. In the third altitudinal range, forest encroachment is practically anecdotic, achieving between 1 and 2 new hectares (Figure 32).

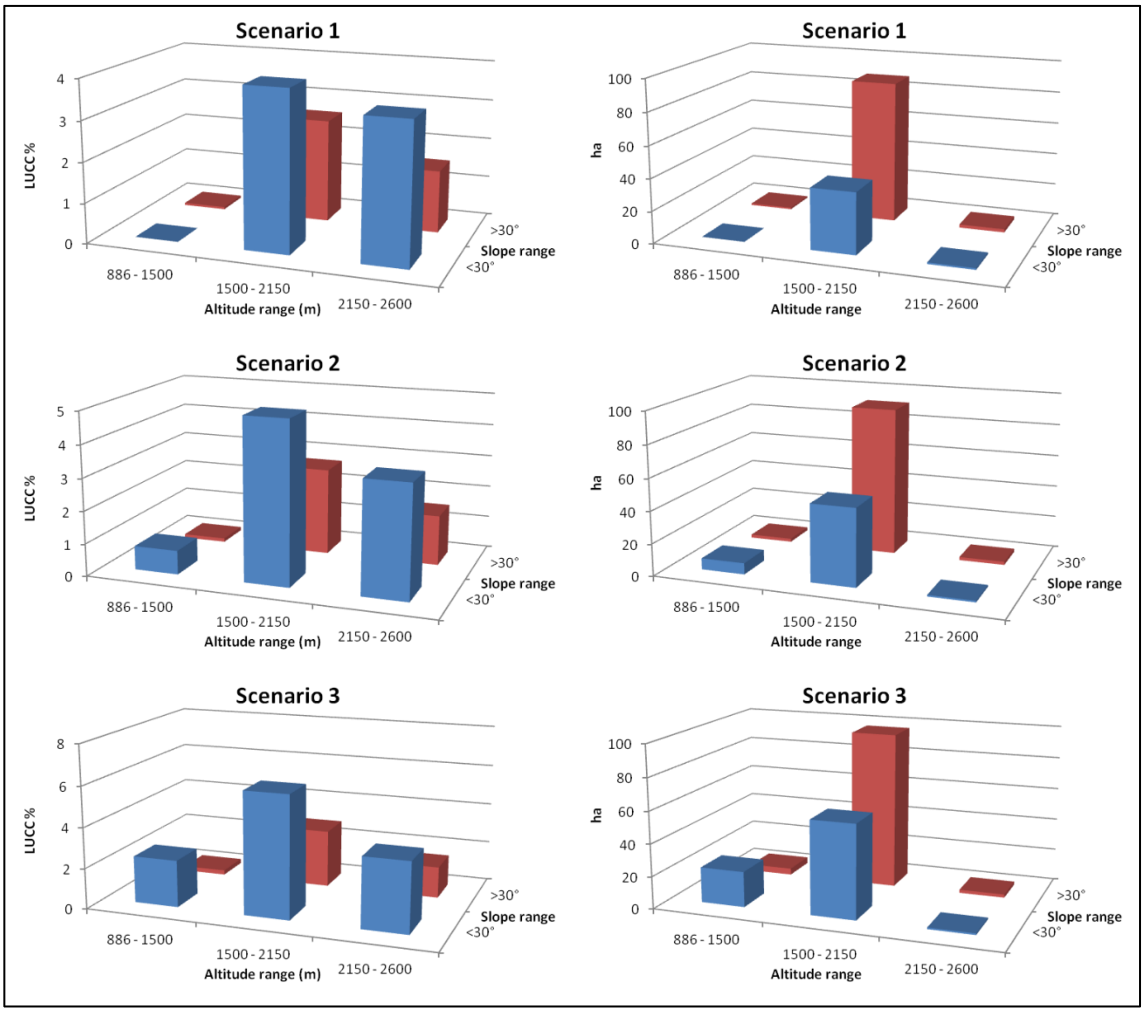


Figure 32: Forest expansion, in percentages and new hectares, differentiated by altitudinal and slope ranges for each simulated scenario from 2003 to 2033.

Chapter 7. Analysis of results by means of Response-Surface Models

"Response-surface methodology comprises a body of methods for exploring for optimum operating conditions through experimental methods." (Lenth, 2009)

Chapter 7

Analysis of the results by means of Response-Surface models

7.1. Introduction

Computational models have emerged relatively recently as tools and do not dispose yet of a statistical analysis to evaluate created models. To overcome this limitation, response-surface models have been used to evaluate the behaviour of the landscape changes (LUCC) based on the outputs of the Population Dynamic P systems (PDP) model proposed in this thesis.

The response-surface methodology comprises a set of mathematical techniques in which a response variable is influenced by different factors of quantitative character. The purpose of these techniques is to design an experiment that contains the possible values the response variable can achieve, and to determine afterwards a mathematical model that is convenient for the obtained data, which can be a first-order (linear) or second-order (quadratic) model. The relationship between the response variable and the factors or variables can be represented by a surface that is called response surface. This is a contour plot of the adjusted surface, in which the values of the response variable are indicated using contour lines within a plan formed by the values of two of the factors or variables of the model (Lenth, 2009).

The aim of response-surface models is to identify what variations in livestock number are statistically significant in landscape changes and, besides, to establish the weight they represent, separately for each considered land use and for each of the study areas.

7.2. Building a response -surface model

In the model building process, firstly, an experimental design is generated and, secondly, the response surface is adjusted. The package ***rsm*** (Lenth, 2009) for R (R Core Team, 2012) was used to carry out these analyses. This package provides several functions to facilitate classical response-surface methods. The rsm package is available at the website of the *Comprehensive R Archive Network* (http://CRAN.R-project.org/package=rsm).

Box-Behnken designs were generated (Box and Behnken, 1960), as they are useful designs for adjusting second order response-surface models. In the phase of model definition, the scenarios to simulate were obtained. These have been simulated by means of the PDP model described in Chapter 4. The design factors are the variables of livestock annual increase or reduction, expressed as probabilities. In all cases, 30 years in the future have been simulated, performing 30 simulation repetitions per year.

The rsm function provides, among others, the estimation of the model's parameters, the coefficient of determination, the table of analysis of variance and the stationary points of response surface (Lenth. 2009). A stationary point is a point in the domain of a function that indicates a maximum, a minimum or a saddle point. A saddle point is defined as a point with a slope of zero, which is neither a maximum nor a minimum of the function. When a saddle point is given, small variations around stationary points do not alter the value of the response variable.

An important aspect of surface-response model building is using codified variables. Coding permits all coded variables in the experiment to vary within the same range. This facilitates the necessary calculations for the model generation and improves its adequacy in estimating the coefficients. The coded variables can vary within the range from -1 to 1. It is necessary to take into account that this range corresponds to the maximum and the minimum value real variables achieve. Therefore it is essential to bear their meaning in mind in order to accomplish a proper interpretation.

7.3. Response-surface models in the Catalan Pyrenees

In the High Catalan Pyrenees the introduced variables or factors to predict the evolution of the surface of the response variable (ha), are the annual increase or reduction of livestock number, expressed as probabilities in each of the considered counties (Table 15). Some values have been provided separately for specific counties, because of different observed trends. This is what happens when, for example, the number of a type of domestic animals is reduced in a certain county, although the general trend in the study area is an increasing census. The most important factors were introduced into the model, simplifying aspects to improve the interpretation of the response-surface model. The response variables of the models show the land-use evolution over 30 years, for the time span 2009-2039.

Table 15: Definition of the factors introduced into the response-surface model. AU: Alt Urgell; AR: Alta Ribagorça; BE: Berguedà; CE: Cerdanya; PJ: Pallars Jussà; PS: Pallars Sobirà; RI: Ripollès; SO:Solsonès; VA: Val d'Aran. Levels are in original units.

Livestock	Factor	Interpretation	Reference counties	Levels (original units)	
				Minimum	Maximum
Sheep and goats	X_1	Decrement	AU, AR, BE, CE, PJ, PS, RI, and SO	-0.1	-0.017
	X_2	Increment/decrement	VA	-0.1	0.035
Cattle	X_3	Increment/decrement	AU, AR, CE, PJ, PS, RI and VA	-0.1	0.043
	X_4	Decrement	SO and Be	-0.1	-0.018
Horses	X_5	Increment/decrement	AU, BE, CE, PJ, PS, RI and SO	-0.1	0.072
	X_6	Decrement/manteniment	AR, Be and VA	-0.1	0

7.3.1. Forest

The model to predict forest evolution includes only the following significant variables: horses X_5 (p<0.01), the interaction between the sheep of the two groups X_1 and X_2 (p<0.05) and the quadratic variation of cattle X_2^2 (p<0.05) (Equation 4). The adjusted coefficient of determination (R^2) is 0.3818. This value indicates that livestock has a significant but not decisive weight in the reforestation of shrublands. This is justified by the fact that the animals have an indirect effect on forest expansion. Stationary values (Table 16) indicate a saddle point of the response surface.

$$Y = 91181 - 156.875X_5 + 166.375X_1X_2 - 226.250X_2^2 \qquad \text{Equation 4}$$

Table 16: Stationary points for the forest response variable in the Pyrenees

Stationary points	X1	X2	X3	X4	X5	X6
Coded values	0.249	-0.029	-0.111	-0.820	-1.299	-0.259
Original units	-0.048	-0.034	-0.036	-0.093	-0.126	-0.063

On the one hand, the fact that the forest expansion depends on sheep, ignoring the effect of cattle, may occur because sheep have the potential to use the whole grazing land independently of the slope, while cows can only graze on flat areas or on gentle slopes. Therefore, annual variations in sheep herds may have a major impact on forest evolution. On the other hand, the reforestation of abandoned farming surfaces depends indirectly on grazing effect. When the animals do not or not completely use a surface, it is considered abandoned and, in the following, shrub and tree communities develop over time. This interpretation explains the low coefficient of determination.

The variations in the number of sheep and goats in Val d'Aran (variable X_2) alone do not have a significant effect on the evolution of forest surface, but their interaction with sheep reduction in other counties (variable X_1) is statistically significant (Figure 33). This figure shows how the forest surface is at its minimum when, both, the increment of one variable and the decrement of the other are maximum. So, the surface becomes minimal when one of the variables reaches its maximum and the other its minimum value. In the case of the Pyrenees with their current trends, the growth of the forest surface originated by a general reduction of sheep X_1 is counteracted by the effect of sheep increase in Val d'Aran X_2.

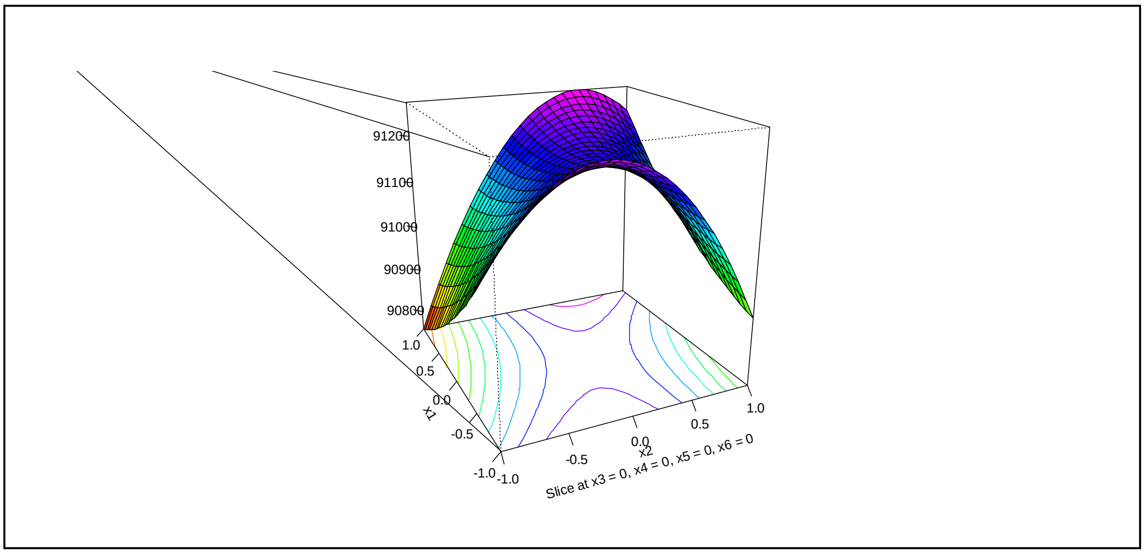


Figure 33: Tridimensional adjusted response-surface contour plots for the forest response variable (ha) in the Pyrenees. The figure shows the effects of the significant interaction (p<0.05) between sheep (X_1 and X_2).

7.3.2. Shrubland

Using the shrubland area obtained at the end of the modelling period as a response variable, the following variables are significant in the resulting model: X_1, X_3, X_5 (p<0.01), the interaction X_2X_4 (p<0.05) and the quadratic part of the model, X_1^2 (p<0.05) and X_3^2 (p<0.001) (Equation 5). The model's coefficient of determination is 0.8894. That is to say that the changing numbers of sheep, cows and horses have, in the regions where they occur, an effect on the surface dominated by shrubs after thirty years. Stationary values (Table 17) indicate a saddle point in the domain of the function.

$$Y = 36164.25 - 116.844X_1 - 734.833X_3 - 216.750X_5 - 155.125X_2X_4 - 159.479X_1^2 - 481.667X_3^2 \quad \text{Equation 5}$$

Table 17: Stationary points for the shrubland response variable in the Pyrenees

Stationary points	X1	X2	X3	X4	X5	X6
Coded values	-0.153	0.440	-0.716	0.993	-0.474	1.352
Original units	-0.065	-0.003	-0.080	-0.018	-0.055	0.018

In this case the shrubby colonization of the formerly pastoral surfaces depends on sheep, cows and horses (X_1, X_3, X_5) and on the interaction of the sheep from Val d'Aran with the cows from Berguedà and Solsonès (X_2X_4). An important fact is that the weight of cow number variations X_3 is much more important than variations regarding the rest of livestock, as can be seen in the values of the parameters, both in first-order and second-order functions. This greater importance can also be observed in the response-surface contour plots, where the variable that represents the increment and decrement of the cows has a greater effect than the ones for sheep and horses (Figure 34).

The interaction between the cows of Berguedà and Solsonès and sheep in Val d'Aran (X_2X_4), forms what is called a minimax, wherat cattle is having a greater weight than sheep, as shown in figure 35. The bush cover becomes minimal when one of the two variables reaches its maximum and the other its minimum value.

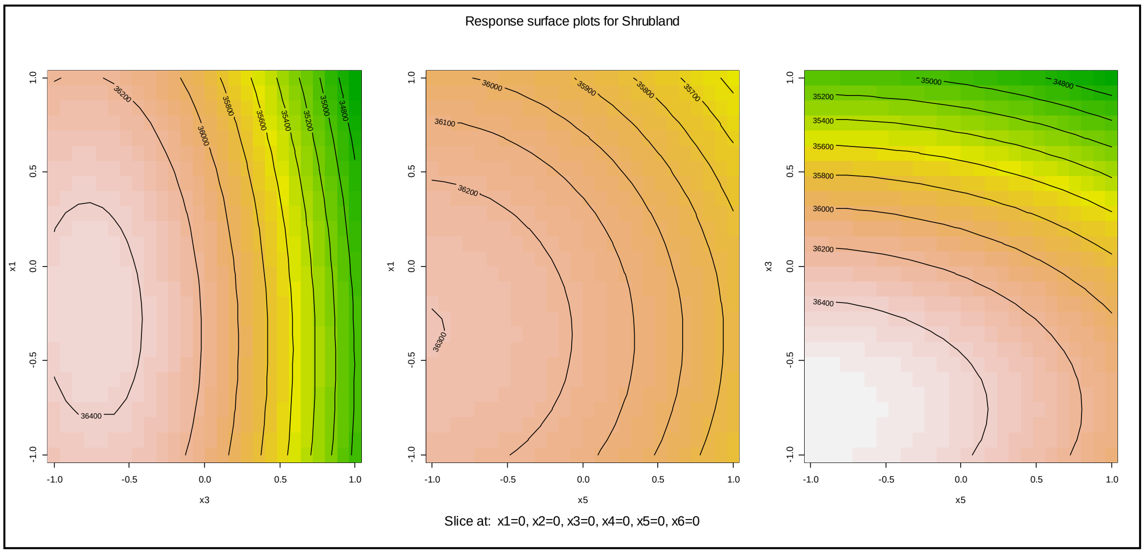


Figure 34: Adjusted response-surface contour plots for the variable response shrubland (ha) in the Pyrenees.

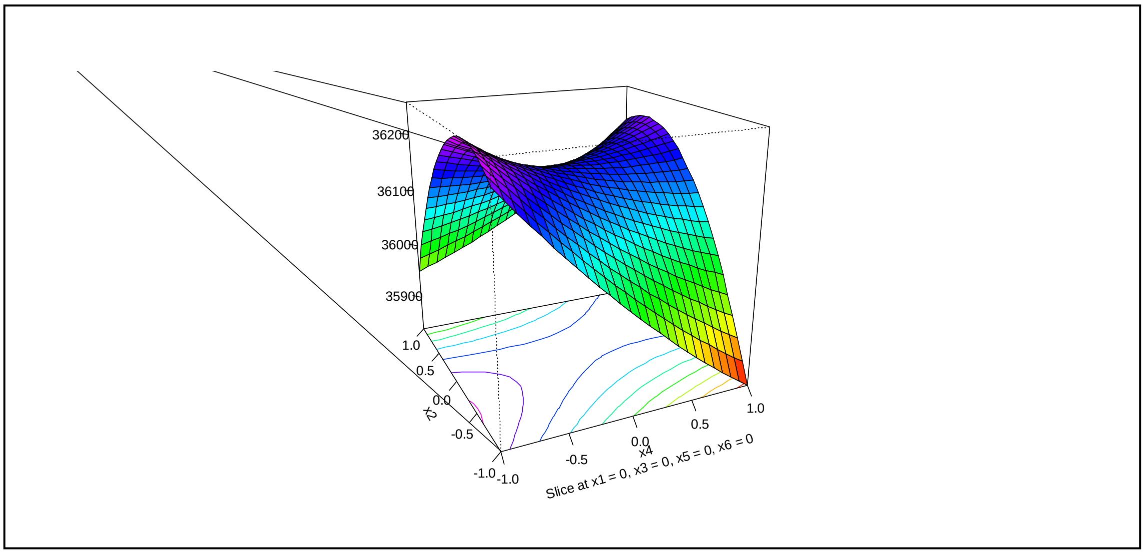


Figure 35: Tridimensional adjusted response-surface contour plots for the shrubland response variable (ha) in the Pyrenees. The figure shows the effects of the significant interaction (p<0.05) between sheep (X_2) and cows (X_4).

7.3.3. Meadows and pastures

With regard to pastures, the obtained model shows a very good coefficient of determination, adjusted R-squared (R^2) is 0.9785, because pastures are directly influenced by the effect of domestic animals, whereat the effect on shrubs and forest is indirect. In this model, the significant predictor variables are X_1, X_3 and X_5 in the first-order (p<0.001) and in the second-order model (p<0.01), as well as the interaction between the factors X_3X_5 (p<0.001). This shows that the annual variations in the number of sheep, cows and horses, which affect the majority of the counties, determine the maintenance or the disappearance of pastures (Equation 6). Stationary values (Table 18) indicate a saddle point in the adjusted response surface.

$$Y = 6462 + 960.53X_1 + 6587.33X_3 + 2233.67X_5 - 1003.50X_3X_5 + 817.33X_1^2 + 3086.08X_3^2 + 1269.71X_5^2 \quad \text{Equation 6}$$

Table 18: Stationary points for the used pastures response variable in the Pyrenees

Stationary points	X1	X2	X3	X4	X5	X6
Coded values	0.010	6.953	-0.923	-0.786	-0.365	-0.054
Original units	-0.058	0.437	-0.094	-0.091	-0.045	-0.053

The coefficients' values indicate, together with figure 36, that the animals that have more weight in the maintenance of grazing lands are cows, followed by horses and finally by sheep. The model confirms that grazing lands are preserved to the extent that the numbers of animals increase, and that pastures become abandoned land when the number of grazers decreases.

The interaction between cows and horses (X_3X_5) is, in this case, highly significant (p<0.001). The explanation for this is that both livestock types graze on the same surfaces in the groups that include a greater number of counties (Figure 37). The combined effect of the number of cows and horses on pasture conservation is more important than the effects they would have individually.

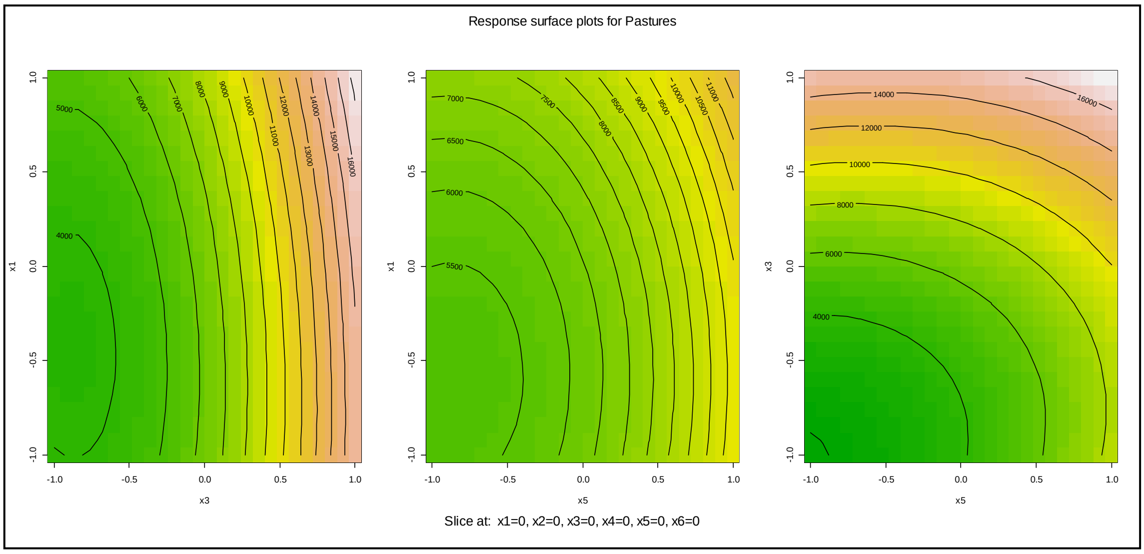


Figure 36: Adjusted response-surface contour plots for the response variable pastures (ha) in the Pyrenees.

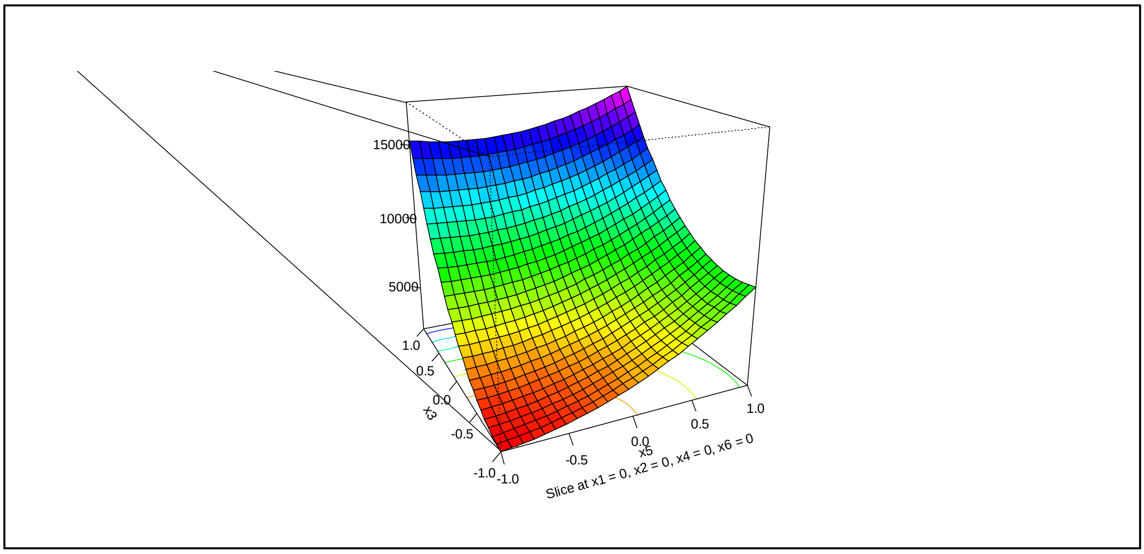


Figure 37: Tridimensional adjusted response-surface contour plots for the response variable pastures (ha) in the Pyrenees. The figure shows the effects of the significant interaction (p<;0.001) between varying numbers of cows (X_3) and horses (X_5).

7.3.4. Abandoned land

The variables that explain the abandonment of pastoral surfaces are the variations in the number of sheep in the whole study area (variables X_1 and X_2) (p<0.01), of cows (X_3) (p<0.001) and horses (X_5) (p<0.001) in the linear part of the model, the interaction between cows and horses (X_3X_5) (p<0.001) and the squares of the variables relating to the variation of the number of sheep, cows and horses $\left(X_1^2, X_3^2, X_5^2\right)$ (p<0.01). In this case a model with a coefficient of determination of 97.85% (adjusted R^2 = 0.9785) was obtained (Equation 7). A saddle point in the response surface is indicated by the stationary values (Table 19).

$$Y = 54222.75 - 834.34X_1 - 421.38X_2 - 4856.96X_3 - 1862.92X_5 + 1108X_3X_5 - 681.17X_1^2 - 2478.92X_3^2 - 1133.79X_5^2 \quad \text{Equation 7}$$

Table 19: Stationary points for the response variable abandonment in the Pyrenees

Stationary points	X1	X2	X3	X4	X5	X6
Coded values	-0.459	0.714	-1.266	-0.046	-1.352	0.252
Original units	-0.078	0.016	-0.119	-0.061	-0.130	-0.037

As the livestock number augments, the abandoned surface diminishes and vice versa. Unlike the observed in the maintenance or abandonment of pastures, the variation of the sheep census in Val d'Aran (X_2) has this time a significant effect. Moreover, as in the model for pastures, variations regarding the number of cattle (X_3) have a greater importance than respective variations in other livestock types. This is shown by coefficient values and the adjusted response-surface contour plots (Figure 38).

The interaction between cows and horses (X_3X_5) is, as in the model for pastures, highly significant (p<0.001). The explanation is the same that has been given before: reducing the numbers of the two livestock types at the same time, increases the abandoned area more importantly than if only one of the two is reduced, given that they share the same summer pastures (Figure 39).

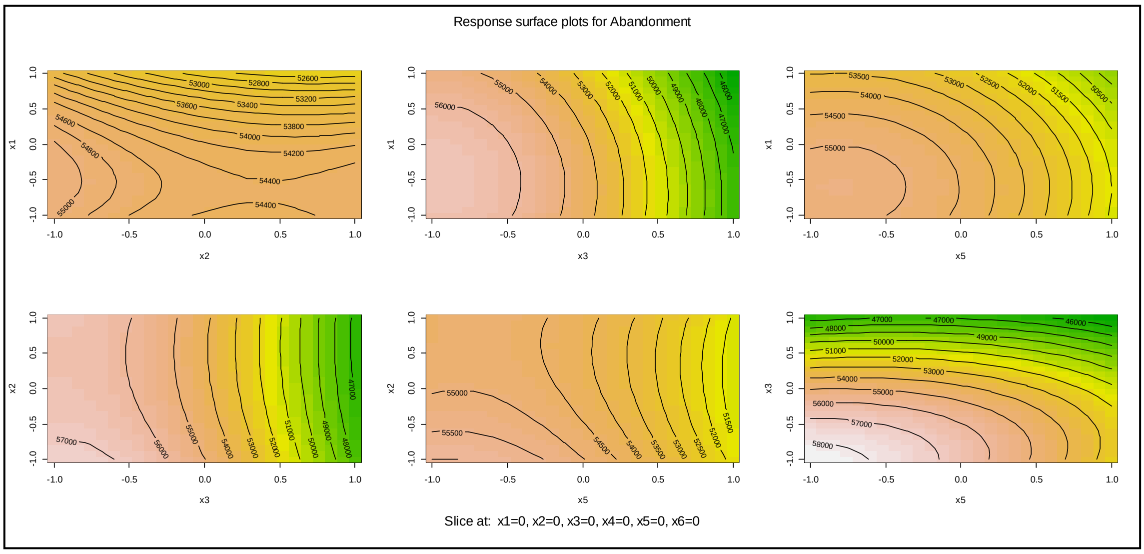


Figure 38: Adjusted response-surface contour plots for the response variable abandoned land (ha) in the Pyrenees.

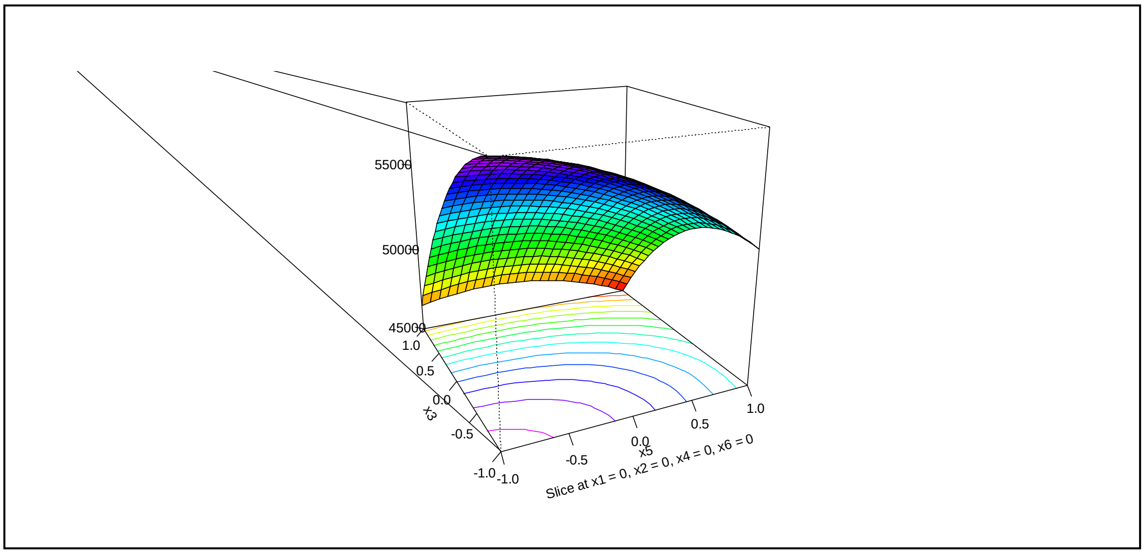


Figure 39: Tridimensional adjusted response-surface contour plots for the response variable abandoned land (ha) in the Pyrenees. The figure shows the effects of the significant interaction (p<0.001) between cows (X_3) and horses (X_5).

7.4. Response-surface models in the Stubai Valley

In the second study area, the Stubai Valley, the predictive variables are the annual census variations of goats X_1, sheep X_2, cattle X_3, and horses X_4, expressed as probabilities. Except for the goats, the variables' values indicate in all cases a decrease of the animal number. Unlike the Pyrenees, all types of domestic animals follow the same trends in both municipalities, so that it has not been necessary to differentiate between villages (Table 20). The response variable, expressed in surface units (ha), is obtained from the degree of variation of the explanatory variables or factors for a time span of 30 years, from 2003 to 2033.

Table 20: Definition of the factors or variables and their levels in the Stubai Valley.

Factor	Livestock	Levels (original units)	
		Minimum	Maximum
X_1	Goats	-0.1	0.008
X_2	Sheep	-0.1	-0.016
X_3	Cows	-0.1	-0.006
X_4	Horses	-0.1	-0.014

7.4.1. Forest

The spontaneous reforestation of forest is affected by the variations of the sheep X_2 (p<0.001), cattle X_3 (p<0.001) and horses X_4 (p<0.05). This is a first-order model with a coefficient of determination of 0.9169 (Equation 8). Stationary values (Table 21) indicate a saddle point in the adjusted response surface.

$$Y = 7423.75 - 7.833X_2 - 18.75X_3 - 2.5833X_4 \quad \text{Equation 8}$$

Table 21: Stationary points for the response variable forest in the Stubai Valley

Stationary points	X1	X2	X3	X4
Coded values	1.168	30.332	44.834	-7.420
Original units	0.017	1.214	2.053	-0.375

As can be seen in the importance of the estimated coefficients and in the contours plots (Figure 40), the increase or decrease of the number of cows has a major effect on forest expansion at the end of the modelling period, followed by variations in the number of sheep and finally of horses. The forest surface depends on abandoned land and, hence, indirectly on the numbers of animals. Thus, it is shown that the forest surface is inversely proportional to the number of domestic animals that graze on mountain pastures. Goats have no effect on the forest evolution, because their numbers are quite low, even though the observed trend in both municipalities is their annual increase.

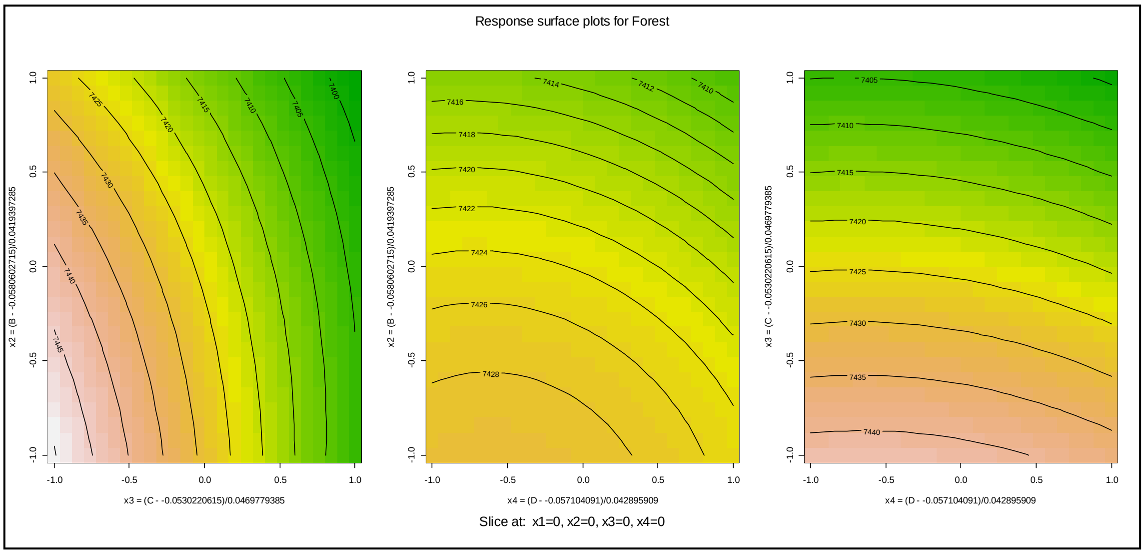


Figure 40: Adjusted response-surface contour plots for the response variable forest (ha) in the Stubai Valley.

7.4.2. Abandoned land

The abandonment of agricultural surface is predicted with a second-order function, in which all variables, except those referring to the variations in the numbers of horses X_4, are significant $X_1, X_2\ i\ X_3$ (p<0.001) and (X_1^2, X_2^2, X_3^2) (p<0.01). Furthermore, the interaction between sheep and horses is also significant X_2X_4 (p<0.05). The model's coefficient of determination is 0.9899 (Equation 9). Stationary values (Table 22) indicate a saddle point in the adjusted response surface.

$$Y = 4492 - 42X_1 - 65.33X_2 - 225.50X_3 + 20.50X_2X_4 - 21.625X_1^2 - 24.875X_2^2 - 95.375105.3X_3^2 \quad \text{Equation 9}$$

Table 22: Stationary points for the response variable abandonment in the Stubai Valley

Stationary points	X1	X2	X3	X4
Coded values	-0.600	-0.167	-1.271	2.195
Original units	-0.078	-0.065	-0.113	0.037

In this case, the effect of the number of animals for the landscape is clearly visible, since it is directly influenced by the grazing and not indirectly, as in the case of forests. The more animals graze the rangelands the lower is the abandonment. Horses do not have a significant effect on the model, probably due to their low numbers, 26 heads in the case of *Fulpmes* and 29 in *Neustift*, and because their numbers are decreasing yearly in all studied scenarios. Likewise, when the livestock units (LU) that represent horses are compared with those of other animals, lower horse LU are obtained in all cases. The coefficients and the adjusted response-surface contour plots show that variations in the number of animals play the most important role in the case of cows (Figure 41).

The study of the interaction that occurs between sheep and horses (Figure 42) manifests that although horses alone do not have a significant effect on the abandonment, they intensify or attenuate the process when they are considered together with the sheep. This behaviour can be explained by the different use that these two grazers make of moderately intensive used grasslands. Sheep can move on the entire surface, whereas horses are only able to move on gentle and moderate slopes (≤30°). So, the reduction of sheep has an effect on the maintenance or the decrease of pastures along the entire surface, while the reduction of horses only affects surfaces on low slopes. Thereby, a small reduction of horses in combination with a severe decrease of sheep, favours the abandonment of grazing land on steeper slopes and the preservation of the agricultural use of the flatter areas. The lower number of horses explains why their reduction does not provoke the same levels of abandonment as in the case of sheep.

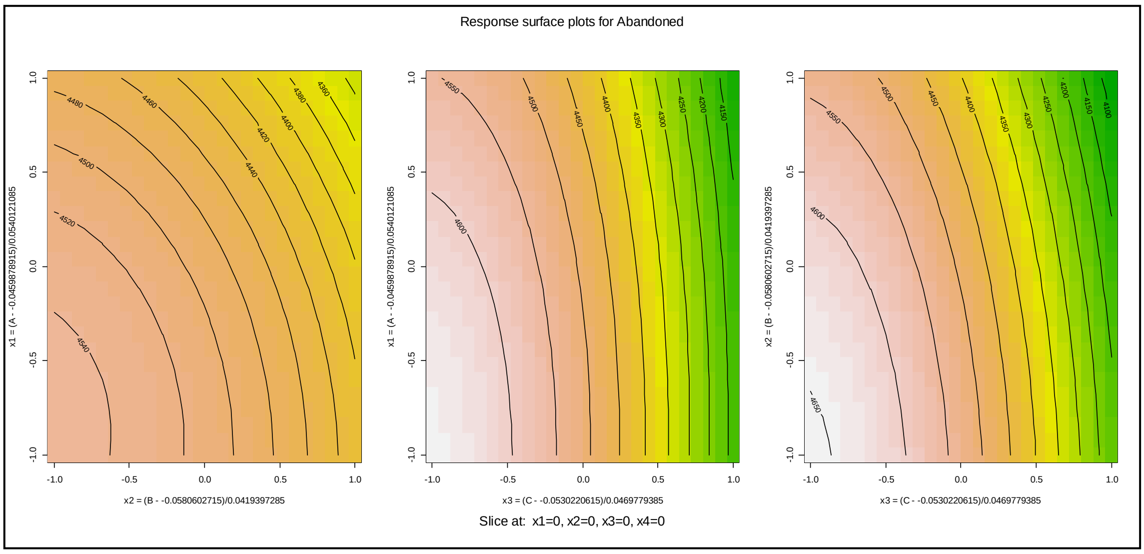


Figure 41: Adjusted response-surface contour plots for the response variable abandoned land (ha) in the Stubai Valley.

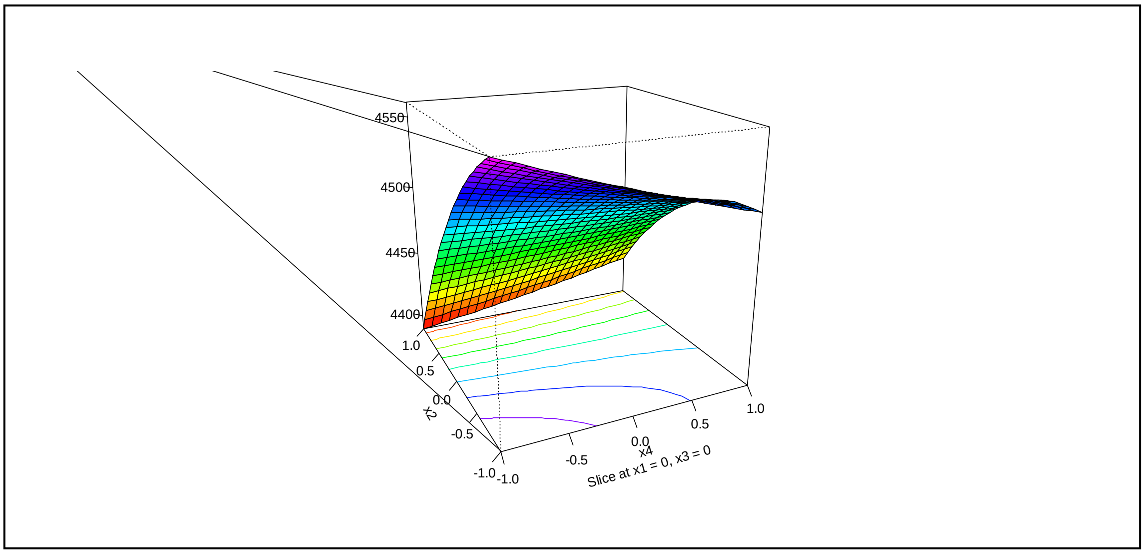


Figure 42: Tridimensional adjusted response-surface contour plots for the response variable abandoned land (ha) in the Stubai Valley. The figure shows the effects of the significant interaction (p<;0.05) between the variation of sheep (X_3) and horses (X_2).

7.4.3. Moderately intensive used grasslands

In the model for the prediction of the moderately intensive used grasslands, variations in the number of all domestic ungulates have a significant effect: X_1, X_2 and X_3 (p<0.001) and X_4 (p<0.05) in the linear part; the interaction between sheep and horses X_2X_4 (p<0.05) and the variables X_1^2 (p<0.05) and X_2^2 and X_3^2 (p<0.001) in the quadratic part of the model. The adjusted coefficient of determination (R^2) is 0.9896 (Equation 10). A saddle point in the adjusted response surface is indicated by the stationary values (Table 23).

$$Y = 152.250 + 11.167X_1 + 18.167X_2 + 72.167X_3 + 3.33X_4 - 7X_2X_4 + 5.833X_1^2 + 9.583X_2^2 + 20.583X_3^2 \qquad \text{Equation 10}$$

Table 23: Stationary points for the response variable moderately intensive used grasslands in the Stubai Valley

Stationary points	X1	X2	X3	X4
Coded values	1.343	7.752	-0.909	24.647
Original units	0.027	0.267	-0.096	1.000

All livestock types take part in the maintenance of the moderately used grasslands, even though with different weights. The bovine stocking rate is, just like in the rest of the created response-surface models, the one with the highest relevance to landscape transformation. The number of horses has a lower importance, as is displayed in the estimated coefficients of the model. This situation is graphically illustrated in figure 43, where the evolution of moderately intensive used grasslands can be observed as a function of annual changes in the livestock number. The surface of moderately used grasslands is directly proportional to the stocking rate: the more severe the animal number is reduced, the greater is the loss of grasslands. On the contrary, increasing the grazing pressure preserves these grasslands.

The interaction that exists between the number of sheep and horses is very similar to that obtained for the abandonment, just the other way around. The maximum and minimum of the function are reached when the reduction of horses is maximum ($X_4 = -1$,) whereat a less severe reduction leads to less extreme values (Figure 44). This interaction is explained similarly as in the case of the abandoned land, just in reverse. The reduction of sheep has an effect on the entire surface, while the reduction of horses only affects pastures located on low and gentle slopes.

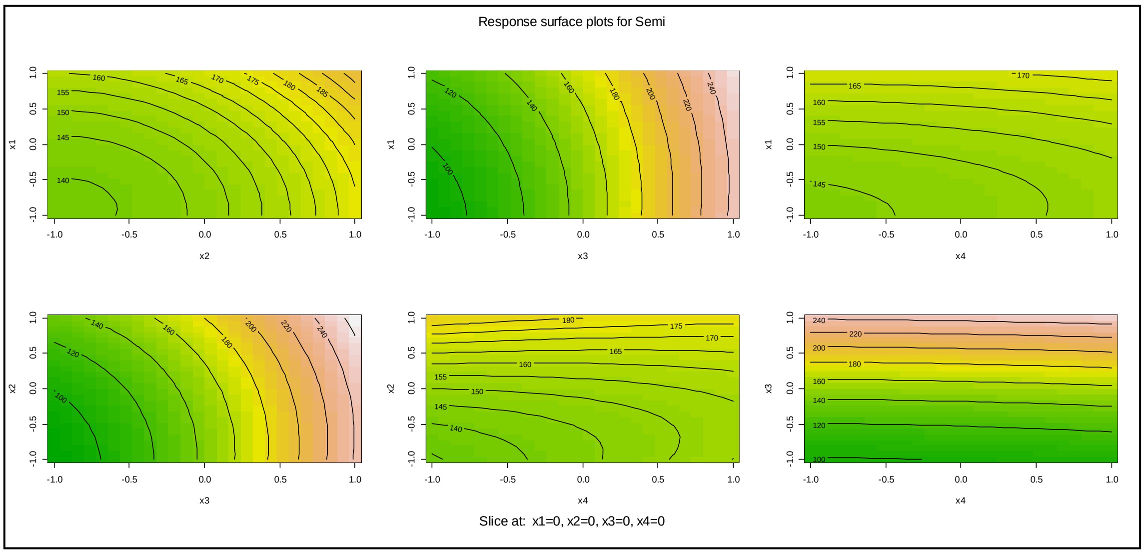


Figure 43: Adjusted response-surface contour plots for the response variable moderately intensive used grasslands (ha) in the Stubai Valley.

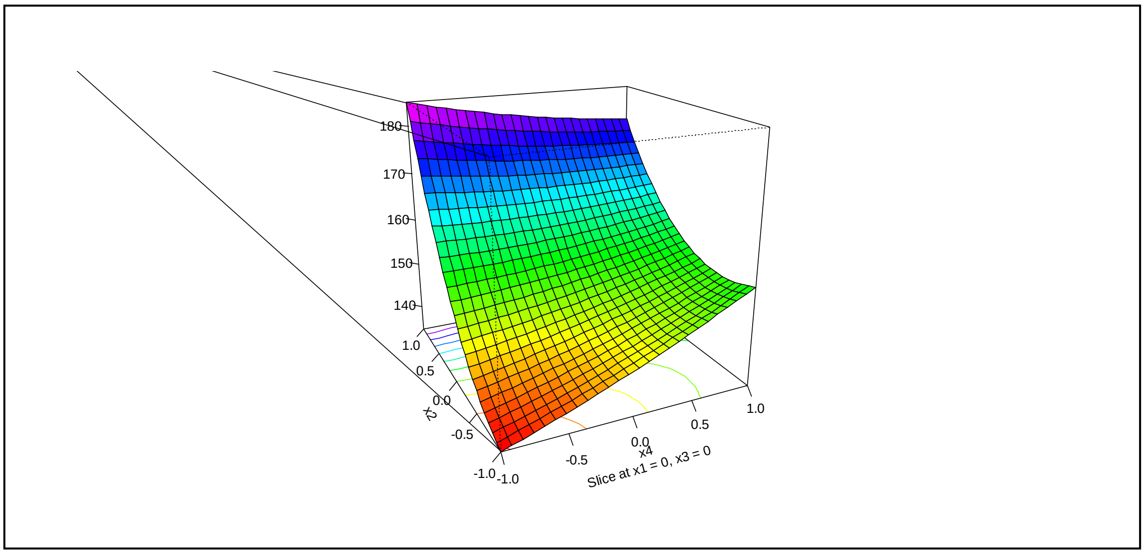


Figure 44: Tridimensional adjusted response-surface contour plots for the response variable moderately intensive used grasslands (ha) in the Stubai Valley. The figure shows the effects of the significant interaction (p<0.05) between variations regarding the numbers of sheep (X_3) and horses (X_2).

7.4.4. Extensively used grasslands

Finally, the model for extensively used grasslands is presented. The variables X_1, X_2 and X_3, (p<0.001) of first-order and X_1^2, X_2^2 and X_3^2 (p<0.01) of second-order are statistically significant. In addition, there are no two-way interactions among significant variables (Equation 11). The prediction power of the model (adjusted R-squared) is 0.9874. Stationary values (Table 24) indicate a saddle point in the domain of the function.

$$Y = 307 + 31.833X_1 + 55.083X_2 + 173.25X_3 + 19.458X_1^2 + 18.083X_2^2 + 77.333X_3^2 \qquad \text{Equation 11}$$

Table 24: Stationary points for the response variable extensively used grasslands in the Stubai Valley

Stationary points	X1	X2	X3	X4
Coded values	-0.169	-0.260	-1.233	2.668
Original units	-0.055	-0.069	-0.111	0.057

In this last case of land-use modelling, the modifications of all livestock types, except horses, have a significant effect on the disappearance or maintenance of meadows and extensive pastures. A possible explanation for this is the before mentioned low number of horses, and the fact that they graze mostly on moderately intensive used grasslands, which are located below the extensively used and are characterized by gentler slopes, being hence more suitable for horses. In spite of the fact that cattle grazes the same grasslands as horses, their high number causes a stronger distribution on the available surface. Variations in the bovine stocking rate have a major impact on the extensively used surfaces, followed by variations regarding sheep and goats. The adjusted response-surface contour plots (Figure 45) show clearly that the increase of cattle is highly relevant for the maintenance of these surfaces.

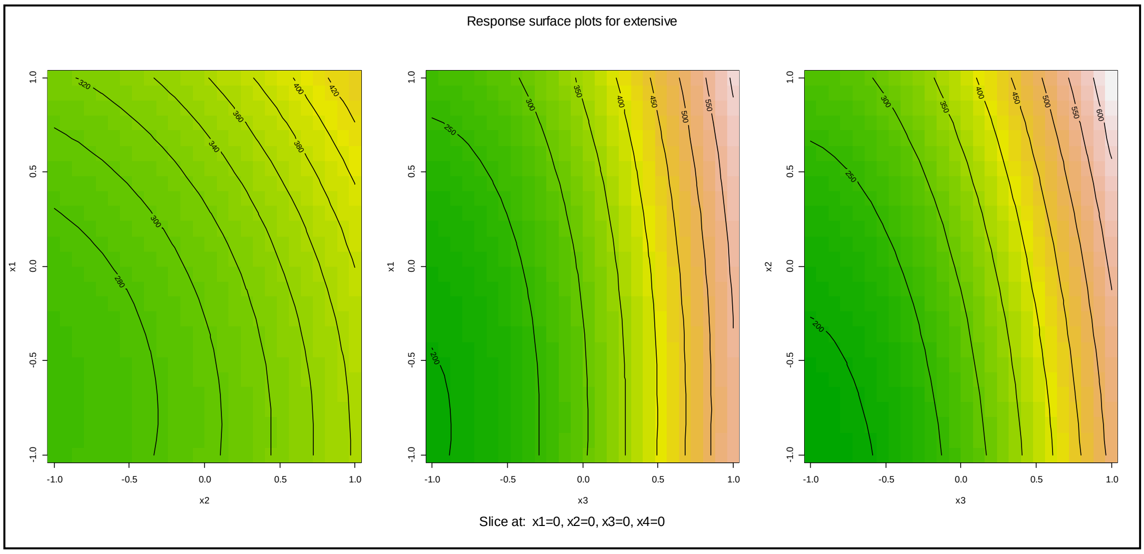


Figure 45: Adjusted response-surface contour plots for the response variable extensively used grasslands (ha) in the Stubai Valley.

Chapter 8. General discussion

"The future of landscape in mountain areas appears to depend on maintaining agro-pastoral farms that alone can manage the land in these difficult environments." (Mottet et al., 2006)

Chapter 8

General discussion

8.1. Designing the PDP model

Since the second half of the 20th century, a spontaneous reforestation and a reduction of the agricultural surface have been observed in most of the European mountain regions. These landscape modifications are caused mostly by land-use changes, especially those related to the abandonment and the extensification of agriculture (MacDonald et al., 2000; Mottet et al., 2006; Tasser and Tappeiner, 2002). The observation of this phenomenon has led to the interest in studying it in detail. In this thesis, a *Population P system model (PDP)* is presented, which facilitates the prediction of *land-use and cover changes* (LUCC), (occurring in subalpine and alpine landscapes, parting from the agricultural land-use intensity). Changes in the agricultural land-use intensity are used as a main variable to predict the LUCC in subalpine and alpine landscapes. So, different future scenarios are simulated in which a large number of animal species and habitats or land covers evolve in parallel and interacting with each other. In these complex ecosystems, in which both human and environmental factors intervene, the PDP models show their full potential (Margalida and Colomer, 2012; Margalida et al., 2011).

In the work at hand, the possible effects of climate change on landscape change have not been taken into account, which influence mainly the reforestation process. Although climate change has a certain influence (D Gómez, 2008; Martínez et al., 2012), land-use changes are considered the major forces leading to landscape modifications (Mottet et al., 2006; Tasser and Tappeiner, 2002). If climate changes were the driving forces, we should observe changes at the tree line, as the changed climate should enable species to grow at higher or lower altitudes. However, the tree line has hardly changed in the last years and the biggest alterations were observed in low and medium altitudes, indicating, hence, that the driving force in these changes were land-use changes and not the climate change (Améztegui et al., 2010). In other words, the most important changes in the structure and density of forests have been observed in areas in which the agricultural activity has been previously abandoned, and not in zones close to the upper limit of the forest, where no forest expansion is detected above the actual tree line due to rise in temperatures.

The present work demonstrates the great potential of the PDP models, showing their potential for becoming a modelling tool of reference in the field of natural ecosystems. In this sense, it is precise to emphasize the large number of agents involved in the model. Up to 9 different animal species and up to 6 different land uses or habitats intervene in the model. These numbers show the model's high potential, which is not at all comparable to classical models, such as differential equations. The fact that ungulates' behaviours can modify their habitat, and that the habitat in turn has an effect on animals, has contributed to take a step forward in the field of modelling with P systems. In the rather short history of P systems, these models have been largely limited to the modelling of population dynamics, not regarding their environments and even less the possibility to modify them (Margalida and Colomer, 2012; Margalida et al., 2011).

Theoretically, the possibilities of the PDP models are immense, the only existing limit is the computational cost that increases with the model's complexity. Therefore, the processes to model must be chosen carefully, in order to achieve the best possible results without an excessive increase of the number of rules, a strategy known as the principle of parsimony. An example to illustrate this fact can be seen in the topographical aspects considered in LUCC modelling. In the framework of this thesis, altitude and slope have been considered, since the slope and the distance from the farmstead are main factors deciding if the agricultural use of mountain parcels continues or is abandoned (Mottet et al., 2006; Tasser and Tappeiner, 2002). However, in the reforestation process, the aspect plays an important role, and is particularly central in the works about the Pyrenees (Améztegui et al., 2010; Lasanta and Vicente-Serrano, 2007), while in the Alps, aspect has a minor importance (Tasser et al., 2007). With these premises, the aspect is a variable that could be introduced in future models. However, it should be considered whether the results improve significantly enough to justify additional rules and the greater computational cost that would be a result of this change. Thanks to the rapid technological development, the limitation of computational costs is becoming a less important challenge even in the most complex models.

This work highlights the multiple potentialities offered by PDP models in studying natural ecosystems. Even though, the thesis has focused on the LUCC, further information can be extracted from the model and may be of interest for studies with different aims. Studying how populations of wild ungulates evolve under certain management measures could be for example highly useful for drafting hunting plans or the protection of endangered species. Furthermore, the model offers information about the amount of forage produced and consumed, so that is possible to calculate the carrying capacity that the environment can sustain. In other words, the proposed PDP model for alpine ecosystems offers numerous possibilities for further application, thanks to the large amount of information introduced and the provided outputs. Moreover, the thesis at hand shows one of the most interesting features of P systems, the relative ease with which new modules can be introduced into the model, without the necessity of major changes, facilitating its adaptation to new situations and study areas.

8.2. The adjustment of the model to the two study areas

The LUCC modelling has been successfully carried out in two study areas in the alpine biogeographical region: one of them located in the Catalan Pyrenees and the other in the Austrian Central Alps, in the Stubai Valley. Usually, it is convenient to construct a specific model for each different case, including the intrinsic features of each study area. However, in this study it was appropriate to build a single model that includes the particularities of both cases, since they have main characteristics in common and share future challenges. The possibility of applying the model in two different mountain regions has demonstrated the flexibility of the PDP model and its ability to adapt to new situations that arise, either by changing the inputs of the model or by adding new modules.

The model was validated by testing its functionality predicting current or past developments, using the inputs from series of historical vegetation and land-use maps. Unfortunately, these are almost nonexistent in the Pyrenees (D Gómez, 2008). Current and future works facilitating the necessary data for the Pyrenees are expected to solve the problem of missing data, so that the study of LUCC, in particular, and of vegetation changes, in general, will become easier in the Pyrenees. In the Stubai Valley, on the contrary, the evolution of the vegetation is widely documented. Habitats and land-use maps exist for the years 1954, 1973, 1988 and 2003, based on the interpretation of georectified aerial photographs and orthophotos, and even for the 19th century maps from the cartographical register of the patrimonial lands of the Habsburg family are available from 1806 to 1869. *Franzian Cartographical Register* (Tappeiner et al., 2008; Tasser et al., 2012c). This availability of data on past changes allows the validation of the model, as correct predictions of past developments ensure the adequacy of future predictions.

It is generally accepted that the modelled processes depend on the spatial scale (Veldkamp and Lambin, 2001). In other words, the processes to be modelled are chosen according to the scale. Therefore, a specific scale is established based on the objective of the model. Although there is an important difference between the surfaces of the two study areas, the methodology used for LUCC modelling is the same, obtaining very good results in both cases. However, the simulations carried out in the Stubai Valley, at the local level, are finer than those made in the Pyrenees, at the regional level, since at regional scale, the modelled processes are more heterogeneous and less control is exercised over the LUCC producing forces. A negative aspect of working on a small scale, for instance at municipal level, is that it is often impossible to observe the LUCC effects (Gellrich et al., 2007). However, this is not the case of the Stubai Valley. In spite of the fact that only two municipalities form the study area, these make up the upper part of the valley, as *Neustift im Stubaital* is one of the largest municipalities in Austria. This shows that PDP models are not limited by the chosen scale and can be employed for local and regional-scale models. However, an appropriate scale of modelling must be chosen depending on the level of detail pursued.

The surfaces where the LUCC processes have been explored are those in which traditional land uses are practiced more or less intensively. Several agricultural surfaces have not been subject to LUCC modelling: intensively used meadows at the valley bottom, existent in the Stubai Valley, and mountain meadows of the Pyrenees, although these are included in the model as producing forage, a part of which is available for the wild ungulates in the case of the Pyrenees. On the one hand, the intensively used meadows at the bottom of the Stubai valley were not considered for landscape changes, as intensification processes are less important than extensification, since abandonment and spontaneous reforestation are the most frequent LUCC happening to mountain grasslands (Rutherford et al., 2008). On the other hand, mountain Pyrenean meadows, many of which have been turned into pastures in recent years, have not been taken into account because of the difficulty to predict their evolution, as well as the small area they represent in the whole study area, which is less than 1% of the total.

The abandonment of agricultural surfaces was the modelled process that was most difficult to introduce into the model. The consulted literature generally estimates the abandonment according to the physical characteristics of the meadows and pastures (Rutherford et al., 2008; Schirpke et al., 2012) and socioeconomic status (Gellrich et al., 2007). In this context, only the work of Gibon et al. (2010) on the French Pyrenees, provides a methodology to estimate land abandonment similar to that proposed in this thesis, from the balance of the grass consumed and produced.

In order to control the correct adjustment of the model, a comparison between the outputs of the model and the data observed in reality has been made, calculating the relative error for each land use. The ideal situation would have been to perform a statistical test for the validation of the model, but this was not possible as only one observation per value was available. Nevertheless, the used method meets the requirements for the purpose of the model and is hence perfectly suitable (Rykiel Jr., 1996). In the two study cases the relative errors are below 10% in all considered land uses, indicating that the model has a high predictive power.

8.3. Future scenarios

The decisive element for developing the future scenarios to model were expert predictions on possible modifications of the European Union's Common Agricultural Policy (CAP), as EU rural funding policies are the usually applied criterion at the European level, especially in mountain areas (Bayfield et al., 2008; Lasanta and Marín-Yaseli, 2007; Renwick et al., 2013; Soliva et al., 2008). This widespread use justifies their application in this work, in both study regions, and allows establishing patterns about the mountain landscape evolution under certain socio-economic conditions. This type of future scenarios are similar to those that have been used by other authors in LUCC modelling in mountain zones (Gibon et al., 2010) or even in one of the considered study areas, the Stubai Valley (Schirpke et al., 2012).

A scenario in which the current livestock farming trend is maintained, *status quo*, allows the landscape evolution modelling in the case of no changes in the agricultural policies in any sense, enabling the evaluation of the current situation. The other two scenarios show what could happen in the event of a decline in support for agriculture and farming. These last scenarios represent extreme situations, as they assume a strong reduction of all the animals. However, both of them serve to illustrate how the modification of grazing pressure has effects on the evolution of the landscape.

Other scenarios have also been proposed in literature, considering diversification and a reduction of some of the restrictions on rural planning, for example in the case of the extension of the construction areas (Bayfield et al., 2008). These approaches have not been taken into account in the present study, as they are little related to the initial idea of modelling landscape changes on the basis of land-use changes, which includes traditional agricultural and livestock farming practices.

Finally, it is important to add that, as Soliva et al. argue (2008), the future will most probably not bring a specific scenario, but a combination of some of the characteristics of each of them.

8.4. LUCC results and analysis

The application of the model in alpine ecosystems highlights the importance of the maintenance of the traditional land uses for the preservation of cultural agricultural landscapes. The results obtained provide a view of the intensity of LUCC that is expected to occur in the future under different scenarios. Although, the results are very similar in both study areas, the LUCC are slightly more intense in the Pyrenees. On the one hand, the results in the *status quo* scenario show in both regions a certain degree of preservation of the cultural landscape, with abandonment and reforestation in marginal areas. On the other hand, landscapes largely dominated by abandoned areas and forest are obtained in scenarios 2 and 3, in which the funding support for agriculture is reduced with respect to the current situation. In the analysis of LUCC in the study areas, the scale affect cannot be disregarded: the Pyrenean case, for its extension, is very heterogeneous. The Stubai Valley, on the contrary, is a highly specific case with its particular features, which do not have to be extrapolated to the rest of the mountain range.

In the Pyrenees, the zones located in medium and low altitudes of the study area, between 1700 and 2600 m, are those that lose a greater proportion of agricultural surface throughout the modelled time span, without differences among slopes except in the third altitudinal range, where the abandonment of grazing land is superior on the steep slopes. A possible explanation for this trend is that most of the pastures on high slopes, which theoretically are the first to disappear (Gibon et al., 2010), have been abandoned in previous years, so that if the reduction of the stocking rate continues, the pastoral surfaces on low and gentle slopes are also abandoned. However, it is important to say, in defence of the obtained results, that Mottet et al. (2006) conclude in their work in the French Pyrenees that the abandonment of parcels is more influenced by their accessibility than by their biophysical conditions or land uses. With regard to forest, the biggest relative expansion occurs between 2200 and 2600 m, but the predicted absolute forest surface is much more important between 1700 and 2200 m of altitude than in the rest of locations. In both situations, the most intense reforestation occurs on low and gentle slopes. These forecasted trends are very similar to those observed in the reality in the study area for the time span 1993-2009 (CREAF, 2013). The works that studied the reforestation in the Pyrenees do not offer a unique conclusion regarding the slope: some observe a more intense forest encroachment at the steeper slopes (Gracia et al., 2011; Poyatos et al., 2003), while others conclude that there are no differences in terms of slope (Améztegui et al., 2010). As for the shrubland, the model predicts a major encroachment on low and moderate slopes. This result contrasts with the work of Komac et al. (2011), in which a higher annual growth rate of dwarf shrubs was obtained for high slopes in the central Pyrenees, although outside the study area and considering other slope ranges. These differences in the consulted works in the Pyrenees depend largely on the physical characteristics of the study area and on the species or plant communities considered in each case, revealing therefore the great heterogeneity of LUCC processes in the mountain range.

In the second study area, the Stubai Valley (Central Alps), the most important loss of meadows and pastures (used grasslands) is expected to occur on the second altitudinal range (1500-2150 m), mostly on high slopes. The largest reforestation rate is predicted in all considered scenarios for the same altitudinal range, but on low slopes. These results are in line with the observations of other authors in the Alps and the Pyrenees. Gellrich et al. (2007), obtained similar results for the Swiss mountain area, where the highest frequencies of forest re-growth, and hence of abandonment of meadows and pastures, occurred at altitudes between 1400 and 2100 m. In addition, it is also widely accepted that the process of land abandonment occurs mainly on steep slopes (Gellrich et al., 2007; Gibon et al., 2010; Taillefumier and Piégay, 2003; Tasser and Tappeiner, 2002). The explanation can be found in the fact that, on the one hand, flat and accessible surfaces are preferred for agricultural uses (Mottet et al., 2006; Tasser and Tappeiner, 2002), and, on the other hand, that the lower altitudes are more intensively used for agriculture and at higher altitudinal ranges, reforestation is limited by environmental conditions, so that the proportion of reforested surface decreases drastically with altitude (Gellrich et al., 2007; Tasser et al., 2007; Zimmermann et al., 2010).

A difference between the Catalan Pyrenees and the Stubai Valley is the uneven development of livestock farming in recent years (Idescat, 2013; Tasser et al., 2013). While in the Pyrenees cattle replace sheep, the Stubai Valley faces a general reduction of all types of domestic animals. Thus it should be expected that, in the *status quo* scenario in the Pyrenees, steep mountain areas, traditionally grazed by sheep, would be gradually abandoned. In the Alps, on the contrary, the livestock stocking rate is homogeneously reduced in the whole surface over the years, without being able to observe a theoretical evolution as clear as in the previous case. However, this development is not clearly seen in the Pyrenees. It is only slightly observed in the highest altitudinal range, above 2600 m.

A remarkable aspect is that, even though the two study areas have different demographic realities, the obtained LUCC results are very similar. According to a study about the agricultural abandonment in European mountain areas by MacDonald et al. (2000), land abandonment is usually associated with rural depopulation in marginal areas. This is the case of the Pyrenees, where the population has been decreasing since the mid-20th century, but it is not the situation of the Stubai Valley. In this alpine valley the opposite is the case. The population has been increasing thanks to the tourism boom, the proximity of important communication routes and of the city of Innsbruck. A possible explanation why, even though the population increases, traditional agricultural practices decline is found in the work of Gellrich et al. (2007) and Gellrich and Zimmerman (2007) in the Swiss mountains and of MacDonald et al. (2000) in Tyrol. The conclusion of the last is that in municipalities with a greater proportion of part-time farmers, i.e. of those who have additionally an off-farm job, farm abandonment and reforestation rates are higher, as less time is invested in the cultivation of marginal lands. The same idea can also be extracted from the farmers' opinions in the Central Western Pyrenees, who claim that, although at present there are more animals than before, shrub and forest encroachment is increasing, because less time is invested in extensive grasslands, controlling their proliferation (Fernández-Giménez and Fillat, 2012). Therefore, while the depopulation is one of the key factors that cause LUCC in the Pyrenees, in the Stubai Valley, the most relevant cause are the changes in the productive sector and the existence of part-time farmers.

The drastic reduction of the agricultural surface and its replacement by abandoned land and woody vegetation, involve changes in the ecosystem services (Fillat et al., 2011; Lamarque et al., 2011; Schirpke et al., 2013a). The modification of this multi-functionality acquires greater importance in the second and in the third simulated scenario of both study zones, in which a high proportion of traditional agricultural landscapes is lost at the end of the modelled period, including, for instance, the species-rich meadows or larch meadows in the Alps (Bolliger et al., 2011). From the point of view of ecology, land-use abandonment produces a reduction of biodiversity (Tasser and Tappeiner, 2002), and from the point of view of the economy a decrease in the quantity and quality of pastures (Lamarque et al., 2011; Marriott et al., 2004). In addition, it is possible to obtain a reduction of water flow of rivers and streams, because it is intercepted by the excess of forest that grows without control (López-Moreno et al., 2013, 2006); and an increase of forest fires (García-Ruiz and Lana-Renault, 2011), especially on the southern slopes of the Pyrenees, with Mediterranean tendency. It is necessary to remember that a large part of the plant communities that can be found in the alpine and subalpine grasslands are listed as natural habitat types of community interest in the annex I of the Habitats Directive, which requires the designation of special areas of conservation for their conservation, some communities even within the category of priority habitat types (Ostermann, 1998). The obtained results indicate that the importance of these effects varies according to the degree of reduction of the agricultural activity.

The impacts of LUCC do not affect only at ecological level, but also at social and cultural level. From the point of view of the aesthetic quality of mountain landscapes, the society prefers cultural landscapes, in which agricultural surfaces coexist with partially reforested spaces (Hunziker et al., 2008; Schirpke et al., 2013a, 2013b; Taillefumier and Piégay, 2003). Following these perceptions, the first simulated scenario, *status quo,* would receive greater social acceptance, while the third scenario, which assumes the virtual disappearance of the traditional agricultural landscape, would achieve the worst rating. However, according to Bacher et al. (2012) the society does not express rejection for extreme scenarios, neither for highly intensified landscapes nor for those dominated by forest. The visual perception associated with a loss of cultural heritage is then very important, because the scenic beauty of the landscape is considered a valuable resource, especially in mountain areas, and is, hence, essential for future developments (Hunziker et al., 2008; Schirpke et al., 2013b).

However, not all LUCC effects observed in the results are negative for the ecosystem. The abandonment and the subsequent reforestation entails certain impacts that can be considered beneficial (Tasser et al., 2007). Example are a greater carbon storage (Bolliger et al., 2008; Hiltbrunner et al., 2013; Schmitt et al., 2010; Tappeiner et al., 2008), an increase in soil stability and a regulation of natural hazards that may occur (García-Ruiz and Lana-Renault, 2011; Tasser et al., 2005, 2003). Therefore, management proposals must pursue a balance between maintaining mountain farming and potentialising the beneficial effects of reforestation in certain areas.

8.5. Analysis of the results by means of Response-Surface Models

In order to complete the study of landscape transformations, response-surface models have been constructed to analyze the behaviour of the model and to know which variables lead to landscape changes. In addition, using classical tools helps to understand the modelled processes and to interpret them more easily than with the use of computational models.

An interesting aspect to comment on is the fact that the equations obtained by means of statistical methods come to the same results as the PDP model, so it can be said that they are included in the model without having been entered explicitly. In other words, the PDP model takes into account and applies analytical expressions, although these remain unknown to the model designer or to the ecologist. This idea was already promoted by other authors in the field of computational modelling (Bousquet and Le Page, 2004).

According to these models, the variable with the most significant weight in landscape changes is the degree of cattle variation, although, cows have no significant effect on forest re-growth in the Pyrenees. These results are consistent, since cattle both for its number and for its nutritional requirements, maintain grazing lands or lead to their abandonment. Moreover, cattle are, just like horses, limited in their mobility to gentle and moderate slopes, so that the livestock heads variations in goat and sheep herds play an important role in landscape changes produced on steep slopes. This situation explains the paradox that in the Pyrenees, even though the total number of animals increases, shrub and forest cover is expanding too, because sheep are being substituted by cattle (Fernández-Giménez and Fillat, 2012).

In the Alps, the results are quite clear, but in the Pyrenees it was necessary to duplicate the factors or explanatory variables to be able to incorporate all the annual increase and decrease tendencies observed in the different counties. Obviously, those variables that include a greater number of counties are of greater importance in landscape changes than those that comprise only few counties. However, variables that represent a reduced number of regions can have a significant effect, when they interact with other variables, modifying the value of the response variable.

The case of reforestation in the Pyrenees, in which livestock plays an important but not decisive role, follows two steps and is explained by the fact that forest re-growth occurs on surfaces previously abandoned and dominated by shrubs, so that the effect of animals is indirect.

With all this, it is important to say that all livestock types considered have a significant effect on the maintenance, abandonment and subsequent reforestation of mountain grasslands, justifying, thus, their selection. Furthermore, the great explanatory power of response variables supports the initial hypothesis that changes in land use are the primary force causing landscape changes.

8.6. Applications of the model in land management

Finally, it can be concluded that the presented model demonstrates satisfactorily the potential of the PDP models applied in the LUCC study in mountain areas. The results evidence the heterogeneous future reduction of traditional land uses in two different study zones and under three different simulated scenarios. Therefore, it is crucial to find new ways to avoid the disappearance of mountain livestock farming and agriculture, because they are the main agents involved in the conservation of traditional landscapes and in the maintenance of the multiple ecosystem services of mountain regions.

The scientific community and the European Union consider the conservation of cultural mountain landscapes through the maintenance of agricultural and livestock activity a priority in the management of alpine landscapes (Fillat, 2003b; Mottet et al., 2006; Pelorosso et al., 2011). Nevertheless, the results do not provide optimism in this respect. All simulated scenarios, in both study areas, predict a progressive reduction of the cultural landscapes, with the consequent loss of associated services provided to the society. At this point, different questions emerge: How can a profitable livestock farming be obtained in disadvantaged areas such as mountain areas? What are the alternatives in a context in which financial support tends to be reduced the future? The option chosen by a considerable number of farms to avoid their disappearance, is diversification (Gellrich and Zimmermann, 2007; Lopez-i-Gelats et al., 2011). However, these adaptations have not been sufficient to avoid landscape changes. In view of the results, the implemented agricultural policies have not had the expected effect, as even in the *status quo* scenario a reduction of cultural landscapes is observed. Moreover, a significant part of the received economic support has failed to fulfil the objective to modernize farms and to improve their production, especially in the case of sheep farming, a sector that continues with a traditional management, very similar to the time before subsidies. The opinion expressed by farmers does not provide much optimism, either. They complain mostly about the excessive bureaucratization of livestock farming, as well as about obligatory sanitary controls that aim to warrant a certain control but complicate the daily life of farmers, involving high economic and time costs. These policies, which expand and become more stringent every year, do not help to maintain the small farms that remain in the high mountains. With this, it is not intended to remove the controls completely, but to recommend that only those that are really essential and useful should be performed.

Therefore, it is necessary to find new and more efficient ways of support in order to preserve traditional land uses and cultural landscapes, the latter being appreciated both by the mountain inhabitants and by tourists (Kianicka et al., 2006). The traditional cultural uses, such as mountain mowing meadows, have been created through an agriculture, a return to which would be an anachronism. Nevertheless, we are still in time for their preservation through extensive farming, the specialization and the implementation of appropriate policies, as for instance the diverse proposed agri-environment measures (Fillat, 2003a, 2003b; Garbarino et al., 2011; Soliva et al., 2008). In this sense, it is recommendable to maintain the most suitable surfaces for traditional agriculture and to promote reforestation in areas where it is useful, for example, due to increased soil stability, or as a carbon storage. In establishing promotion policies, high mountain farms should be considered, on all accounts, as a "special" case, because their reality is very different from the practices at lower altitudes, with more favourable conditions for agriculture and livestock farming, although they are often located in the same municipality. The future reforms of the European Common Agricultural Policy (CAP) can be a good opportunity to find a profitable way for mountain farming and to correct imbalances before it is too late. In these reforms, it is always essential to bear in mind the farmers, as they are the principal managers of these surfaces and their services for the ecosystems should be explicitly recognized. Other stakeholders to consider are the local population or tourists. Eventually, as claimed by Daugstad et al. (2006), livestock farming and agriculture must not only be protected to preserve the multiple ecosystem services, but also because the associated cultural heritage contributes to endow an "identity" to the society.

Chapter 9. Conclusions and future work

Chapter 9

Conclusions and future work

Finally, in the last chapter, the conclusions that can be drawn from this work are presented, as well as some of the research lines to follow in future works.

9.1. Conclusions

Conclusion 1

A PDP model has been built, which is capable of modelling the landscape changes in high mountain regions as a result of land-use changes (LUCC) in order to predict their future evolution. For the first time, habitats and their evolutions have been introduced in the animals' population dynamics, so that P systems modelling has taken a step forward.

Conclusion 2

The PDP model has been applied in two different alpine study areas, demonstrating its flexibility to adapt to different realities and at different work scales. The achievement of this objective indicates the possibility of applying the model in other mountain zones with similar features and challenges, as is the case of most of the mountain ranges in Europe.

Conclusion 3

The variations of the number of goats, sheep, mares and, especially, cattle have a significant effect on the model, explaining the changes that occur in the landscape. This fact supports the hypothesis that land-use changes are the main force that leads to the maintenance or abandonment of the meadows and pastures, as well as, indirectly, their natural reforestation.

Conclusion 4

The obtained results demonstrate that the abandonment of meadows and pastures and their spontaneous reforestation, is inversely proportional to the amount of grazing animals. In addition, the type of animal is important in determining those areas that are abandoned and those that continue with an agricultural use, especially with regard to sheep and cattle. So, according to the tendency that experiment the censuses of different livestock types, the landscape evolves in a different way.

Conclusion 5

In certain locations that are unsuitable for the agricultural practice, the spontaneous forest expansion can be a desirable advantage, as it entails benefits regarding the multiple ecosystem services. In this sense, the pastoral character of the most suitable surfaces should be maintained and the forest re-growth should be allowed in those areas where it is advisable due to its features.

Conclusion 6

In all simulated scenarios, it is observed that the meadows and pastures will be reduced significantly in the near future, coming to disappear in some cases. This contrasts with the existing determination to preserve the pastoral habitats. Therefore, all the stakeholders involved in mountain management need to reach a consensus and to take decisions, leading to the application of effective policies for the conservation of mountain farming. Otherwise, within a few years, mountain farming may eventually disappear, and with it, much of the cultural landscape of alpine mountains.

Conclusion 7

As a general conclusion, the computational modelling with P systems has proved to be a tool with high potential in the field of ecological modelling, in which many challenges exist and increasingly require more precise responses in order to be managed properly. This work is hopefully one step forward in the preservation of alpine worlds and wishes to help ensuring their adaptation to the new times, since only knowing how the landscape will evolve in the future, adequate measures to avoid or reduce negative developments can be carried out.

9.2. Future work

The work on this thesis may have finished, but the work with P systems and on high mountain ecosystems has to continue in the future. On the one hand, further work is necessary in order to complete and improve the knowledge of the modelling with P systems and, on the other hand, to enhance the knowledge on the ecological functioning of high mountain ecosystems.

It is necessary to…

1. Find new ways to reduce the number of model rules and at the same time its complexity and its computational cost.

2. Study the incorporation of the effects of climate change: Along with land-use changes, climate change is the other force that leads to landscape modifications, although to a lesser extent than the first.

3. Introduce land-use intensification processes. In the work at hand, only land-use extensification processes have been considered, as they are the most common in mountain regions. However, the intensification of agricultural surfaces has an importance in certain areas, such as in the valley bottom, as has been seen in the Stubai Valley.

4. Consider the aspect in LUCC modelling. In addition to slope and altitude, aspect has an importance when determining changes that occur in the landscape, particularly with regard to reforestation. Therefore, the possibility to include this variable should be evaluated in future models.

5. Represent the results graphically. Once the results are obtained, the creation of a map is recommended in which the changes occurring in the plant covers can be explicitly appreciated over time. This is a resource used increasingly in LUCC studies, which in addition to identifying and quantifying the changes in the landscape, explicitly indicates where they have occurred.

6. Include diversification of uses as a possible future scenario, an alternative to land-use intensification and extensification, because it is also a scenario considered by the stakeholders. Diversification includes aspects such as the reduction of the limitations imposed in the mountain regions that restrict their possible development.

7. Obtain other types of results. The PDP model presented in this thesis has aimed at identifying and quantifying LUCC in alpine regions. Nevertheless, this model allows obtaining other types of results, depending on the pursued objective, as for example to study the dynamics of wild ungulates or the maximum carrying capacity of the mountain rangelands.

8. Apply the model in other areas. The use of the PDP model is recommended for other regions, in order to contribute to the knowledge on landscape changes in other mountain ranges with similar challenges.

9. Delve into the study of mountain ecosystems. Last but not least, the knowledge on mountain ecology must be continued in order to better understand the processes that occur and, in the field of ecological modelling, to use this new information to improve the models that will be developed in the future.

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Annex A. Inputs and parameters of the model

Annex A

Inputs and parameters of the model

In this annex, all inputs and parameters introduced in the PDP model are provided, both for the study case of the Pyrenees and for the Stubai Valley.

Pyrenees

Table A1: Description of the input and parameters used in the model for the Pyrenees

Symbol	Definition
$g_{i,1}$	1 wild animal and 0 domestic animals
$g_{i,2}$	Age when adult size is reached
$g_{i,3}$	Age when fertility begins
$g_{i,4}$	Age when fertility ends
$g_{i,5}$	Average life expectancy in the ecosystem
k_1	Percentage of females present in the population
k_2	Fertility ratio
k_3	Number of descendants per fertile females that reproduce
m_1	Natural mortality ratio in first years, age < g_2
m_2	Mortality ratio in adult animals, age > g_2
h_1	Percentage of male adult animals hunted
h_2	Percentage of female adult animals hunted
h_3	Percentage of young animals hunted
f_i	Animals' energetic requirements (kg DM day^{-1})
pf_{ijs}	Grazing preferences of the species *i* in land use *l* and on slope *s*
pm_{iuv}	Possibility that the animal *i* moves from the environment *u* to *v*
p_{1i}	Population of the species *i* in the administrative district *k*
d_{ik}	Maximum carrying capacity, species *i*, environment *k*
$Incr_{i,k,y}$	Percentage of annual increase of the species *i*, environment *k* and year *y*
$Decr_{i,k,y}$	Percentage of annual decrease of the species *i*, environment *k* and year *y*
$G_{i,k}$	Percentage of domestic grazers in environment *k*
$S_{l,a,s,k}$	Surface (ha) of land use *l*, altitude *a* and slope *s* in environment *k*
μR_l	Average plant production (kg DM ha^{-1} y^{-1}) in land use *l*
σR_l	Standard deviation of plant production in land use *l*
$\mu T_{l,a}$	Average length of the growing season in land use *l* and altitudinal range *a*
$\sigma T_{l,a}$	Standard deviation of the growing season in land use *l* and altitudinal range *a*
ug_l	Percentage of grasslands used in land use *l*
mw_l	Percentage of available grass after mowing in land use *l*
δ_k	Summation of all the surfaces of environment *k*
rp_s	Reforestation probability in altitudinal range *a*
rp_f	Shrub encroachment probability in altitudinal range *a*
fs	Hectares of burned shrubland
ft	Hectares of burned forest
NZ	Values of a normal distribution *N*(0,1)

Table A2: Values of the parameters used in the model for ungulates

Species	$g_{i,1}$	$g_{i,2}$	$g_{i,3}$	$g_{i,4}$	$g_{i,5}$	k_1	k_2	k_3	m_1	m_2	h_1	h_2	h_3	f_i	$G_{i,k}$
Cervus elaphus	1	1	2	20	20	0.50	0.75	1	0.31	0.06	0.3	0	0	200	1
Capreolus capreolus	1	1	1	10	10	0.67	1.00	1	0.51	0.06	0	0	0	60	1
Rupicapra rupicapra	1	1	2	18	18	0.55	0.75	1	0.52	0.06	0.3	0	0	80	1
Dama dama	1	1	2	12	12	0.75	0.55	1	0.44	0.06	0	0	0	80	1
Ovis musimom	1	1	2	12	12	0.50	0.90	2	0.52	0.06	0	0	0	100	1
Capra aegagrus	0	1	2	8	8	0.96	0.75	1	0.15	0.03	0	0	0	100	0.9
Ovis aries	0	1	2	8	8	0.96	0.75	1	0.15	0.03	0	0	0	100	0.9
Bostaurus	0	2	2	9	9	0.90	0.90	1	0.06	0.05	0	0	0	700	0.9
Equus caballus	0	3	3	9	20	0.97	0.90	1	0.03	0.01	0	0	0	700	0.9

Table A3: Maximum carrying capacity of wild ungulates considered in the Pyrenees (d_{ik})

Species	A. Urgell	A. Ribagorça	Berguedà	Cerdanya	P. Jussà	P. Sobirà	Ripollès	Solsonès	V. d'Aran
Cervus elaphus	1000	70	1000	200	1250	800	250	70	2750
Capreolus capreolus	850	250	1300	850	1000	2000	650	250	1700
Rupicapra rupicapra	650	2000	2000	850	600	4000	4000	650	2000
Dama dama	40	30	0	0	50	950	0	30	0
Ovis musimon	100	0	0	50	0	600	500	50	0

Table A4: Grazing probabilities of ungulate species in the Pyrenees (pf_{ijs}). 0 not available for grazing; 1 on high and low slopes; 2 only on low slopes

Land use	*C. elaphus*	*C. capreolus*	*R. rupicapra*	*D. dama*	*O. musimom*	*C. aegagrus*	*O. aries*	*B. taurus*	*E. caballus*
Forest	1	1	0	1	0	0	0	0	0
Shrubland	1	1	0	1	0	0	0	0	0
Used pastures	1	0	1	1	1	1	1	2	2
Agricultural areas	0	0	0	0	0	1	1	2	2
Open spaces with little or no vegetation	1	0	1	1	1	0	0	0	0
Abandoned land	1	0	1	1	1	0	0	0	0

Table A5: Probabilities that animals change the environments in the Catalan counties (pm_{iuv})

County	A. Urgell	A. Ribagorça	Berguedà	Cerdanya	P. Jussà	P. Sobirà	Ripollès	Solsonès	V. d'Aran
Alt Urgell	1	0	1	1	1	1	0	1	0
Alta Ribagorça	0	1	0	0	1	1	0	0	1
Berguedà	1	0	1	1	0	0	1	1	0
Cerdanya	1	0	1	1	0	0	1	0	0
P. Jussà	1	1	0	0	1	1	0	0	0
P. Sobirà	1	1	0	0	1	1	0	0	1
Ripollès	0	0	1	1	0	0	1	0	0
Solsonès	1	0	1	1	0	0	0	1	0
Val d'Aran	0	1	0	0	0	1	0	0	1

Table A6: Land-use parameters introduced into the model in the Pyrenees

Land use	μR_l	σR_l	Altitudinal range 1		Altitudinal range 2		Altitudinal range 3		ug_l	mw_l
			μT_l	σT_l	μT_l	σT_l	μT_l	σT_l		
Forest	17.37	4.34	131	12	79	7	49	5	0.5	1
Shrubland	5.79	1.45	131	12	79	7	49	5	0.5	1
Used pastures	57.92	14.48	131	12	79	7	49	5	0.5	1
Agricultural areas	69.50	17.37	131	12	79	7	49	5	0.5	0.4
Open spaces with little or no vegetation	5.79	1.45	131	12	79	7	49	5	0.5	1
Abandoned land	11.58	2.90	131	12	79	7	49	5	0.5	1

Table A7: Reforestation (shrubland and forest) probabilities in the Pyrenees

Altitudinal range	Shrubland (*rps*)	Forest (*rpf*)
1. 1700-2200 m	0.01	0.013
2. 2200-2600 m	0.01	0.013
3. >2600 m	0	0

Table A8: Observed burned hectares in the time span 2004-2011

Percentiles	Forest (ha)	Shrubs (ha)	Percentiles	Forest (ha)	Shrubs (ha)
0-50	0	0	76	1	4
51	0	1	77	1	5
52	0	1	78	1	6
53	0	1	79	1	6
54	0	1	80	1	6
55	0	1	81	1	7
56	0	1	82	2	7
57	0	1	83	2	9
58	0	1	84	2	10
59	0	1	85	3	10
60	0	1	86	3	12
61	0	2	87	6	16
62	0	2	88	8	22
63	0	2	89	11	24
64	0	2	90	12	26
65	0	2	91	13	27
66	0	2	92	23	32
67	0	2	93	25	41
68	0	2	94	28	52
69	0	2	95	29	61
70	0	2	96	36	67
71	1	2	97	38	82
72	1	2	98	71	84
73	1	2	99	95	101
74	1	2	100	390	260
75	1	3	-	-	-

Table A9: Ungulate censuses in the Pyrenees for the year 1993

County (1993)	Wild ungulates					Livestock			
	C. elaphus	*C. capreolus*	*R. rupicapra*	*D. dama*	*O. orientalis*	*C. aegagrus*	*O. aries*	*B. taurus*	*E. caballus*
A. Urgell	175	98	395	20	70	1168	17571	2399	308
A. Ribagorça	12	30	1185	13	0	374	19384	2146	152
Berguedà	163	151	1185	0	0	1030	9416	2498	143
Cerdanya	35	98	513	0	20	518	7050	4679	1476
P. Jussà	222	106	355	26	0	1331	37490	1775	186
P. Sobirà	140	235	2449	474	500	1678	33884	3394	1012
Ripollès	42	76	2449	0	350	1605	19034	11339	1075
Solsonès	12	30	395	13	30	827	8017	777	60
V. d'Aran	490	197	1224	0	0	413	3995	737	351

Table A10: Ungulate censuses in the Pyrenees for the year 2009

County (2009)	Wild ungulates					Livestock			
	C. elaphus	*C. capreolus*	*R. rupicapra*	*D. dama*	*O. orientalis*	*C. aegagrus*	*O. aries*	*B. taurus*	*E. caballus*
A. Urgell	851	766	508	29	70	1494	15576	4001	434
A. Ribagorça	57	236	1525	19	0	513	12483	2559	*223*
Berguedà	794	1179	1525	0	0	694	7274	3084	85
Cerdanya	170	766	661	0	20	385	5163	5871	2163
P. Jussà	1078	825	458	38	0	1651	27647	2847	835
P. Sobirà	681	1827	3153	687	500	1246	25142	6700	2118
Ripollès	204	589	3153	0	350	1318	12201	14585	1344
Solsonès	57	236	508	19	30	627	5599	637	77
V. d'Aran	2382	1532	1576	0	0	354	4489	799	499

Table A11: Land-use surfaces (ha) differentiated by slope and altitudinal r anges in the Pyrenees for the year 1993

County	Land use (1993)	1700-2200 m	2200-2600 m	>2600 m	1700-2200 m	2200-2600 m	>2600 m
		Slope range <30°			Slope range >30°		
Alt Urgell	Forest	11717	209	0	1177	62	0
	Shrubland	2484	219	0	971	58	0
	Used pastures	2887	1896	87	116	387	11
	Agricultural areas	357	0	0	0	0	0
	Open spaces with little or no vegetation	288	475	74	170	238	9
	Abandoned land	0	0	0	0	0	0
Alta Ribagorça	Forest	1968	275	0	1949	254	0
	Shrubland	1393	203	3	705	186	3
	Used pastures	3141	2891	345	971	1225	121
	Agricultural areas	11	0	0	0	0	0
	Open spaces with little or no vegetation	392	2603	1232	331	1303	635
	Abandoned land	0	0	0	0	0	0
Berguedà	Forest	3929	44	0	834	14	0
	Shrubland	939	78	0	790	36	0
	Used pastures	2522	762	0	245	121	0
	Agricultural areas	5	0	0	0	0	0
	Open spaces with little or no vegetation	212	281	0	171	63	0
	Abandoned land	0	0	0	0	0	0
Cerdanya	Forest	7976	1200	0	908	182	0
	Shrubland	1770	272	7	190	62	2
	Used pastures	1769	2551	895	29	210	57
	Agricultural areas	214	0	0	0	0	0
	Open spaces with little or no vegetation	190	1126	370	152	345	113
	Abandoned land	0	0	0	0	0	0
Pallars Jussà	Forest	1218	0	0	300	0	0
	Shrubland	1618	212	11	460	84	1
	Used pastures	2173	2102	268	667	566	46
	Agricultural areas	18	0	0	0	0	0
	Open spaces with little or no vegetation	237	1854	629	157	656	196
	Abandoned land	0	0	0	0	0	0
Pallars Sobirà	Forest	16337	1174	1	4543	599	0
	Shrubland	7472	2920	10	3535	847	8
	Used pastures	7859	8388	542	1923	2501	287
	Agricultural areas	122	0	0	2	0	0
	Open spaces with little or no vegetation	962	5807	1920	564	2786	1138
	Abandoned land	0	0	0	0	0	0
Ripollès	Forest	3510	83	0	693	40	0
	Shrubland	1748	226	0	148	32	0
	Used pastures	6145	2895	164	496	374	32
	Agricultural areas	8	0	0	0	0	0
	Open spaces with little or no vegetation	387	1725	623	310	492	166
	Abandoned land	0	0	0	0	0	0
Solsonès	Forest	1634	39	0	266	0	0
	Shrubland	302	28	0	300	1	0
	Used pastures	771	108	0	39	1	0
	Agricultural areas	41	0	0	0	0	0
	Open spaces with little or no vegetation	116	259	0	65	0	0
	Abandoned land	0	0	0	0	0	0
Val d'Aran	Forest	3629	154	0	2623	84	0
	Shrubland	4329	1744	11	2100	406	3
	Used pastures	8414	6546	115	2935	1465	28
	Agricultural areas	59	0	0	2	0	0
	Open spaces with little or no vegetation	588	2832	633	601	1171	245
	Abandoned land	0	0	0	0	0	0

Table A12: Land-use surfaces (ha) differentiated by slope and altitudinal ranges in the Pyrenees for the year 2009

County	Land use (2009)	1700-2200 m	2200-2600 m	>2600 m	1700-2200 m	2200-2600 m	>2600 m
		Slope range ≤30°			Slope range >30°		
Alt Urgell	Forest	12959	320	0	1268	80	0
	Shrubland	2024	139	1	793	56	0
	Used pastures	2282	1527	85	89	231	12
	Agricultural areas	87	0	0	0	0	0
	Open spaces with little or no vegetation	382	831	81	290	376	8
	Abandoned land	0	0	0	0	0	0
Alta Ribagorça	Forest	2189	377	0	2053	366	0
	Shrubland	1655	186	0	724	119	0
	Used pastures	2478	2421	338	611	987	143
	Agricultural areas	9	0	0	0	0	0
	Open spaces with little or no vegetation	565	2978	1259	565	1506	631
	Abandoned land	1	0	0	0	0	0
Berguedà	Forest	4409	84	0	962	21	0
	Shrubland	610	26	0	559	27	0
	Used pastures	2236	634	0	160	85	0
	Agricultural areas	0	0	0	0	0	0
	Open spaces with little or no vegetation	393	427	0	356	102	0
	Abandoned land	0	0	0	0	0	0
Cerdanya	Forest	8680	1639	1	946	219	0
	Shrubland	1148	629	25	106	106	17
	Used pastures	1569	1974	934	41	173	90
	Agricultural areas	177	0	0	0	0	0
	Open spaces with little or no vegetation	272	916	347	188	300	67
	Abandoned land	8	0	0	0	0	0
Pallars Jussà	Forest	1383	0	0	359	0	0
	Shrubland	1423	174	1	614	73	0
	Used pastures	2106	2123	303	359	511	81
	Agricultural areas	0	0	0	0	0	0
	Open spaces with little or no vegetation	367	1805	611	249	725	170
	Abandoned land	0	0	0	0	0	0
Pallars Sobirà	Forest	17601	1487	0	5020	743	0
	Shrubland	6903	2651	6	3966	1114	8
	Used pastures	6994	8533	761	887	2397	391
	Agricultural areas	54	0	0	2	0	0
	Open spaces with little or no vegetation	1148	5599	1713	716	2503	1038
	Abandoned land	0	0	0	0	0	0
Ripollès	Forest	4428	119	0	753	47	0
	Shrubland	1982	313	2	334	136	1
	Used pastures	4980	3279	440	309	434	92
	Agricultural areas	0	0	0	0	0	0
	Open spaces with little or no vegetation	391	1243	366	246	322	106
	Abandoned land	0	0	0	0	0	0
Solsonès	Forest	1917	65	0	290	1	0
	Shrubland	231	8	0	266	1	0
	Used pastures	472	274	0	6	0	0
	Agricultural areas	0	0	0	0	0	0
	Open spaces with little or no vegetation	243	91	0	110	1	0
	Abandoned land	0	0	0	0	0	0
Val d'Aran	Forest	4406	202	0	3169	97	0
	Shrubland	4741	1511	0	2046	343	1
	Used pastures	7037	6045	146	2133	1358	47
	Agricultural areas	40	0	0	3	0	0
	Open spaces with little or no vegetation	873	3471	608	907	1334	227
	Abandoned land	0	0	0	0	0	0

Stubai Valley

Table A13: Description of the inputs and parameters used in the model for the Stubai Valley

Symbol	Definition
$g_{i,1}$	1 wild animal and 0 domestic animals
$g_{i,2}$	Age when adult size is reached
$g_{i,3}$	Age when fertility begins
$g_{i,4}$	Age when fertility ends
$g_{i,5}$	Average life expectancy in the ecosystem
k_1	Percentage of females present in the population
k_2	Fertility ratio
k_3	Number of descendants per fertile females that reproduce
m_1	Natural mortality ratio in first years, age < g_2
m_2	Mortality ratio in adult animals, age > g_2
h_1	Percentage of male adult animals hunted
h_2	Percentage of female adult animals hunted
h_3	Percentage of young animals hunted
f_i	Animals' energetic requirements (kg DM day^{-1})
pf_{ijs}	Grazing preferences of the species *i* in land use *l* and on slope *s*
pm_{iuv}	Possibility that the animal *i* moves from the environment *u* to *v*
p_{1i}	Population of the species *i* in the municipality of *Fulpmes*
p_{2i}	Population of the species *i* in the municipality *Neustift im Stubaital*
d_{ik}	Maximum carrying capacity, species *i*, environment *k*
$Incr_{i,k,y}$	Percentage of annual increase of the species *i*, environment *k* and year *y*
$Decr_{i,k,y}$	Percentage of annual decrease of the species *i*, environment *k* and year *y*
$G_{i,k}$	Percentage of domestic grazers in environment *k*
$S_{l,a,s,k}$	Surface (ha) of land use *l*, altitude *a* and slope *s* in environment *k*
μR_l	Average plant production (kg DM ha^{-1} day^{-1}) in land use *l*
σR_l	Standard deviation of plant production in land use *l*
$\mu T_{l,a}$	Average length of the growing season in land use *l* and altitudinal range *a*
$\sigma T_{l,a}$	Standard deviation of the growing season in land use *l* and altitudinal range *a*
ug_l	Percentage of grasslands used in land use *l*
mw_l	Percentage of available grass after mowing in land use *l*
δ_k	Summation of all the surfaces of environment *k*
rp_a	Reforestation probability in altitudinal range a
NZ	Values of a normal distribution *N*(0,1)

Table A14: Values of the parameters regarding ungulates. N: *Neustift im Stubaital*; F: *Fulpmes*

Species	$g_{i,1}$	$g_{i,2}$	$g_{i,3}$	$g_{i,4}$	$g_{i,5}$	k_1	k_2	k_3	m_1	m_2	h_1	h_2	h_3	f_i	$G_{i,k}$		d_{iq}	
															N	F	N	F
Cervus elaphus	1	1	2	15	15	0.5	0.8	1	0.02	0.02	0.15	0.2	0.2	550	1	1	916	68
Capreolus capreolus	1	1	1	10	10	0.5	0.8	2	0.35	0.08	0.3	0.3	0.2	66	1	1	589	131
Rupicapra rupicapra	1	1	2	12	12	0.5	0.8	1	0.005	0.01	0.1	0.07	0.01	88	1	1	1443	102
Capra aegagrus	0	1	2	8	8	0.96	0.75	1	0.15	0.03	0	0	0	110	1	1	0	0
Ovis aries	0	1	2	8	8	0.96	0.75	1	0.15	0.03	0	0	0	110	1	1	0	0
Bos taurus	0	2	2	9	9	0.9	0.9	1	0.06	0.05	0	0	0	770	0.85	0.35	0	0
Equus caballus	0	3	3	9	20	0.97	0.9	1	0.03	0.01	0	0	0	770	1	1	0	0

Table A15: Grazing probabilities of ungulate species in the Stubai Valley (pf_{ijs}). 0 not available for grazing; 1 on high and low slopes; 2 only on low slopes

Land use	*C. elaphus*	*C. capreolus*	*R. rupicapra*	*C. aegagrus*	*O. aries*	*B. taurus*	*E. caballus*
Forest	1	1	0	0	0	0	0
Abandoned land	1	1	1	0	0	0	0
Agriculturally non-usable area	1	0	1	0	0	0	0
Intensively used grasslands	0	0	0	0	0	0	0
Moderately intensive used grasslands	1	0	0	1	1	2	2
Extensively used grasslands	1	0	1	1	1	2	2

Table A16: Land-use parameters introduced in the model in the Stubai Valley

Land use	μR_l	σR_l	Altitudinal range 1		Altitudinal range 2		Altitudinal range 3		Altitudinal range 4		ug_l	mw_l
			μT_l	ug_l	μT_l	σT_l	μT_l	σT_l	μT_l	σT_l		
Forest	2.38	3.29	199.53	11.94	152.88	15.26	101.57	14.87	50.03	17.90	0.5	1
Abandoned land	4.48	1.17	199.53	11.94	152.88	15.26	101.57	14.87	50.03	17.90	1	1
Agriculturl non-usable area	17.29	7.24	199.53	11.94	152.88	15.26	101.57	14.87	50.03	17.90	0.5	1
Intensively used grasslands	28.11	6.35	199.53	11.94	152.88	15.26	101.57	14.87	50.03	17.90	1	0
Moderately intensive used grasslands	13.66	2.89	199.53	11.94	152.88	15.26	101.57	14.87	50.03	17.90	1	0.60
Extensively used grasslands	6.88	1.79	199.53	11.94	152.88	15.26	101.57	14.87	50.03	17.90	1	0.75

Table A17: Reforestation probabilities in the Stubai Valley

Altitudinal range	Forest (*rpa*)
1. 886-1500 m	0.0991
2. 1500-2150 m	0.0026
3. 2150-2600 m	0.0001
4. >2600 m	0

Table A18: Ungulate censuses in the Stubai Valley for the years 1973 and 2003

Year	Municipality	Wild ungulates			Livestock			
		C. elaphus	*C. capreolus*	*R. rupicrapa*	*C. aegagrus*	*O. aries*	*B. taurus*	*E. caballus*
1973	Fulpmes	45	131	100	1	234	416	2
	Neustift i.S.	456	495	1259	211	600	1290	16
2003	Fulpmes	45	131	100	63	476	332	26
	Neustift i.S.	456	495	1259	652	1897	1152	29

Table A19: Land-use surfaces (ha) differentiated by slope and altitudinal ranges in the Stubai Valley for the year 1973

Municipality	Land use (1973)	886-1500 m	1500-2150 m	2150-2600 m	>2600 m	886-1500 m	1500-2150 m	2150-2600 m	>2600 m
		Slope range ≤30°				Slope range >30°			
Neustift i.S.	Forest	628	797	29	0	1379	2732	117	0
	Arable land	0	0	0	0	0	0	0	0
	Abandoned land	15	382	602	0	22	1090	1305	12
	Agriculturally non usable area	0	17	623	48	0	30	573	128
	Intensively used grassland	675	7	0	0	80	3	0	0
	Moderately intensive used grassland	56	248	0	0	10	34	0	0
	Extensively used grassland	21	560	230	0	54	638	320	3
Fulpmes	Forest	287	92	0	0	327	335	8	0
	Arable land	25	0	0	0	0	0	0	0
	Abandoned land	6	4	0	0	3	1	0	0
	Agriculturally non usable area	0	0	0	0	0	1	25	0
	Intensively used grassland	219	0	0	0	12	0	0	0
	Moderately intensive used grassland	11	5	0	0	1	2	0	0
	Extensively used grassland	0	2	0	0	0	6	2	0

Table A20: Land-use surfaces (ha) differentiated by slope and altitudinal ranges in the Stubai Valley for the year 2003

Municipality	Land use (2003)	886-1500 m	1500-2150 m	2150-2600 m	>2600 m	886-1500 m	1500-2150 m	2150-2600 m	>2600 m
		Slope range ≤30°				Slope range >30°			
Neustift i.S.	Forest	652	867	29	0	1448	3072	119	0
	Arable land	0	0	0	0	0	0	0	0
	Abandoned land	1	520	755	0	2	1100	1558	15
	Agriculturally non usable area	0	17	623	48	0	30	573	128
	Intensively used grassland	666	8	0	0	74	10	0	0
	Moderately intensive used grassland	63	185	0	0	4	16	0	0
	Extensively used grassland	13	414	77	0	17	299	65	0
Fulpmes	Forest	298	97	0	0	331	340	10	0
	Arable land	0	0	0	0	0	0	0	0
	Abandoned land	0	0	0	0	0	0	0	0
	Agriculturally non usable area	0	0	0	0	0	1	25	0
	Intensively used grassland	216	0	0	0	12	0	0	0
	Moderately intensive used grassland	7	4	0	0	0	1	0	0
	Extensively used grassland	0	2	0	0	0	3	0	0

Annex B. Livestock's annual increase and decrease probabilities

Annex B

Livestock's annual increase and decrease probabilities

This Annex provides the probabilities of annual variations in the animal number. The structure is the same for both study areas: firstly, the observed evolution are displayed and, secondly, the values for each simulated scenario.

Pyrenees

Table B1: Annual animal increase or decrease probabilities observed for 1993-2009 and assumed for the different future scenarios 2009-2039 (Catalan counties)

Time span		County	Increase				Decrease			
			Goat	Sheep	Cattle	Horses	Goat	Sheep	Cattle	Horses
Observed	1993-1999	Alt Urgell	0.000	0.008	0.057	0.000	0.007	0.000	0.000	0.009
		Alta Ribagorça	0.086	0.000	0.021	0.084	0.000	0.038	0.000	0.000
		Berguedà	0.032	0.003	0.068	0.000	0.000	0.000	0.000	0.011
		Cerdanya	0.012	0.000	0.034	0.042	0.000	0.022	0.000	0.000
		Pallars Jussà	0.000	0.000	0.055	0.143	0.025	0.013	0.000	0.000
		Pallars Sobirà	0.000	0.002	0.045	0.036	0.000	0.000	0.000	0.000
		Ripollès	0.000	0.000	0.036	0.009	0.009	0.014	0.000	0.000
		Solsonès	0.061	0.000	0.035	0.012	0.000	0.017	0.000	0.000
		Val d'Aran	0.020	0.000	0.000	0.061	0.000	0.038	0.007	0.000
Observed and *status quo* scenario	Observed 2000-2009 *Status quo* 2009-2039	Alt Urgell	0.029	0.000	0.018	0.040	0.000	0.017	0.000	0.000
		Alta Ribagorça	0.000	0.000	0.005	0.000	0.017	0.021	0.000	0.010
		Berguedà	0.000	0.000	0.000	0.000	0.057	0.027	0.018	0.044
		Cerdanya	0.000	0.000	0.002	0.013	0.036	0.018	0.000	0.000
		Pallars Jussà	0.037	0.000	0.015	0.072	0.000	0.022	0.000	0.000
		Pallars Sobirà	0.000	0.000	0.043	0.054	0.029	0.031	0.000	0.000
		Ripollès	0.000	0.000	0.004	0.017	0.014	0.035	0.000	0.000
		Solsonès	0.000	0.000	0.000	0.019	0.061	0.025	0.039	0.000
		Val d'Aran	0.000	0.035	0.013	0.000	0.027	0.000	0.000	0.000
Scenario 2	2009-2039	All counties	0.000	0.000	0.000	0.000	0.050	0.050	0.050	0.050
Scenario 3			0.000	0.000	0.000	0.000	0.100	0.100	0.100	0.100

Stubai Valley

Table B2: Annual animal increase or decrease probabilities observed for 1973-2010 and assumed for the different future scenarios 2003-2033 (Stubai Valley)

Time span		Municipality	Increase				Decrease			
			Goat	Sheep	Cattle	Horses	Goat	Sheep	Cattle	Horses
Observed	1973-1999	Fulpmes	0.165	0.031	0.000	0.101	0.000	0.000	0.008	0.000
		Neustift im Stubaital	0.042	0.048	0.000	0.026	0.000	0.000	0.004	0.000
Observed and *status quo* scenario	Observed 2000-2010	Fulpmes	0.008	0.000	0.000	0.000	0.000	0.016	0.006	0.016
	Status quo 2003-2033	Neustift im Stubaital	0.008	0.000	0.000	0.000	0.000	0.016	0.006	0.014
Scenario 2	2003-2033	Stubai Valley	0.000	0.000	0.000	0.000	0.050	0.050	0.050	0.050
Scenario 3			0.000	0.000	0.000	0.000	0.100	0.100	0.100	0.100

Annex C. Conclusions i treball futur (Català)[1]

[1] This Annex is the Catalan translation of *Chapter 9: Conclusions and future work*.

Annex C

Conclusions i treball futur

Finalment en el darrer capítol es presenten les conclusions que es poden extreure del present treball, així com algunes de les línies d'investigació a seguir en treballs futurs.

Conclusions

Conclusió 1

S'ha construït un model PDP capaç de modelitzar els canvis ocorreguts en el paisatge d'alta muntanya com a conseqüència de canvis en els usos del sòl (LUCC) per preveure la seva evolució futura. Per primer cop s'ha introduït l'hàbitat i les seves evolucions a les dinàmiques de les poblacions animals, amb què es dóna una passa més en la modelització amb P sistemes.

Conclusió 2

El model PDP s'ha aplicat a dues àrees d'estudi alpines diferents, demostrant la seva flexibilitat per adaptar-se a diferents realitats i a diferents escales de treball. L'assoliment d'aquest objectiu manifesta la possibilitat d'aplicar el model en altres zones de muntanya amb característiques i reptes similars, com és el cas de la major part de les serralades europees.

Conclusió 3

Les variacions del nombre de cabres, d'ovelles, d'egües i, especialment, de vaques tenen un efecte significatiu en el model, explicant els canvis que es produeixen en el paisatge. Aquest fet recolza la hipòtesi que els canvis en els usos del sòl són la principal força que origina el manteniment o abandonament dels prats i pastures, així com indirectament la seva reforestació natural.

Conclusió 4

Els resultat obtinguts demostren que l'abandonament dels prats i de les pastures i la seva reforestació espontània, és inversament proporcional a la quantitat d'animals que les peixen. A més, el tipus d'animal és important a l'hora de determinar quines zones s'abandonen i quines continuen amb un ús agrícola, sobretot pel que fa a les ovelles i les vaques. Així, en funció de la tendència que experimentin els censos dels diferents tipus d'animals domèstics, el paisatge evolucionarà de manera diferent.

Conclusió 5

En certes localitzacions no aptes per a la pràctica de l'agricultura es poden aprofitar els beneficis que comporta la reforestació espontània en relació als serveis que aporta a l'ecosistema. En aquest sentit, hom ha d'intentar mantenir el caràcter pastoral de les zones més aptes i permetre la recolonització pel bosc en aquelles zones on sigui aconsellable per les seves característiques.

Conclusió 6

En tots els escenari simulats s'observa com en un futur proper els prats i pastures es reduiran de manera important, arribant a desaparèixer segons el cas. Aquest fet contrasta amb la voluntat existent de conservar els hàbitats pastorals. Per tant, si no es prenen decisions consensuades entre tots els actors implicats en la gestió i s'apliquen polítiques eficaces de conservació de la ramaderia d'alta muntanya, en uns anys aquesta pot arribar a desaparèixer, i, amb ella, gran part del paisatge cultural de muntanya alpina.

Conclusió 7

Com a conclusió general, la modelització computacional amb P sistemes ha demostrat ser una eina amb elevades potencialitats en el camp de la modelització ecològica, àmbit en què existeixen molts reptes que requereixen cada cop de respostes més precises per a ser gestionats correctament. Amb aquest treball es té el convenciment d'haver realitzat un pas endavant cap a la preservació del món alpí i garantir la seva adaptació als nous temps, car només coneixent com evolucionarà el paisatge en el futur es poden realitzar les actuacions per a evitar o reduir els impactes negatius que comporta.

Treball futur

Un cop finalitzat el present treball, hom té en convenciment que l'aplicació dels P sistemes sobre ecosistemes de muntanya s'ha de continuar en el futur. D'una banda per completar i millorar el coneixement de la modelització amb P sistemes i de l'altra, per millorar el coneixement del funcionament ecològic dels de ecosistemes naturals d'alta muntanya.

És necessari...

1. Trobar noves vies que permetin reduir el número de regles del model i al mateix temps la seva complexitat i el seu cost computacional.

2. Estudiar la incorporació de l'efecte del canvi del canvi climàtic. Juntament amb els canvis en els usos del sòl, el canvi climàtic és l'altra força que origina canvis en el paisatge, tot i que de manera menys important que els primers.

3. Introduir el procés d'intensificació de l'agricultura. En el present treball s'ha introduït el procés d'extensificació al ser aquest el més comú a les regions de muntanya. Tot i això la intensificació de les superfícies agrícoles té una importància en certes zones, com per exemple els fons de vall, com s'ha vist al cas d'estudi de la Vall de Stubai.

4. Considerar la variable orientació en la modelització dels LUCC. Addicionalment a la pendent i a l'altitud, l'orientació té una importància a l'hora de condicionar els canvis que es produeixen en el paisatge, sobretot pel que fa a la reforestació. Per tant, s'ha de valorar la possibilitat d'incloure aquest variable en models futurs.

5. Presentar els resultats gràficament sobre un mapa. Un cop obtinguts els resultats, és recomanable la creació d'un mapa en el qual s'apreciïn els canvis ocorreguts en les cobertes vegetals al llarg dels anys. Aquest és un recurs cada cop més utilitzat en

l'estudi dels LUCC, que a més a més de identificar i quantificar els canvis en el paisatge, indica explícitament on s'han produït.

6. Incloure la diversificació d'usos com a possible escenari futur, a mode d'alternativa a la intensificació i a la extensificació, al tractar-se d'un dels escenaris considerats pels experts. Aquesta diversificació inclou aspectes com la reducció de les limitacions imposades a les zones de muntanya que restringeixen el seu possible desenvolupament.

7. Obtenir altres tipus de resultats. El model PDP presentat en aquesta tesi s'ha encarat a la identificació i a la quantificació dels LUCC en regions alpines. Tot i això, aquest mateix model permet obtenir altres tipus de resultats, em funció del objectiu que es persegueixi, com per exemple estudiar la dinàmica dels ungulats salvatges o la capacitat de càrrega màxima de les pastures supraforestals.

8. Aplicar el model en altres àrees. Es proposa utilitzar el model PDP en altres àrees per contribuir al coneixement dels canvis en el paisatge en altres serralades amb reptes similars.

9. Aprofundir en l'estudi dels ecosistemes de muntanya. Finalment, cal continuar incrementant el coneixement de l'ecologia de muntanya per tal de comprendre millor els processos que es produeixen i, dins de l'àmbit de la modelització, utilitzar aquesta informació per millorar els models que es desenvolupin en el futur.