LIFE MIDMACC

Mid-mountain adaptation to climate change

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Socioeconomic evaluation of adaptation measures of mid mountain zone

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Executive summary

This report evaluates the socioeconomic impacts of different land-intervention measures proposed by the project MIDMACC to mitigate the effects of climate change in three mid mountain regions of Spain. In particular, it evaluates the effect of the regaining pastureland for extensive livestock keeping, different forest management regimes that rely on periodical clearing of the forest understory and the plantation of vineyards. This report evaluates the efficiency, effectivity and the costs and benefits of these intervention measures and its potential for replicability. For its assessment, the report focuses on the current and future effects of climate change on the socio-economic consequences on the availability of water resources, the fixation of the population in the territory and the reduction of the risk and the spread of wildfires, and the accounting of avoided CO_2 emissions.

The results show that the well-defined land-intervention measures are effective. For instance, clearing shrublands in the analysed region in La Rioja reduced the probability of wildfire by approximately 70%. The costs avoided per hectare burned by the shrubland clearing policy is around 1,400 € per hectare. The generated hydric resources (blue water) increase for all considered climate change scenarios of up to 4 hm^3, resulting in notable economic gains in some of the analysed areas. For example, in Catalonia it represents in terms of an increase in GDP benefits of around 4,900 € per hectare intervened. Apart from the intervention measures in the territory, the report offers a tool that allows to evaluate the effectiveness and efficiency of other measures to reduce the spread of wildfires.

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1. Introduction

The main objective of LIFE MIDMACC project is to promote the adaptation of different landscape management regimes that help mitigate the impact of climate change in the mid-mountain marginal areas of the Iberian Peninsula (La Rioja, Aragon and Catalonia) and improve the socioeconomic development of these areas. During the course of the project, different management measures have been designed in the territory that help mitigate the impact of climate change: the recovery of pastures for extensive livestock, the periodic cleaning of the undergrowth and the cultivation of the vineyard, with the aim of evaluating their ecological and socioeconomic impacts. This report focuses on the socio-economic aspects of land management measures, including their potential to promote economic activity within mid-mountain marginal areas.

The actions carried out in this project are precisely in the third year of experimentation, which makes it difficult to analyze in detail its socioeconomic effectiveness. In addition, the incidence of these measures is very restricted in space, making it difficult to detect the possible impacts that these measures generate in the socioeconomic field. Thus, faced with this double difficulty, similar measures are evaluated that are developed in the three autonomous communities participating in the MIDMACC project.

The report evaluates adaptation measures for reducing fire risk and population fixation, for reducing the spread of wildfires, and for increasing water resources, in terms of criteria of efficiency, effectiveness, cost-benefit and replicability. For each of the three groups of measures, the four criteria are formulated more precisely so that they are measurable and that they allow their diagnosis to be made.

Based on empirical data, the second chapter of this report evaluates the socioeconomic aspects of the periodic cleaning of the understory to reduce the spread of wildfires, as well as the impact of these thinning on the fixation of population in the territory. The third chapter develops and implements a theoretical model in a computer program to evaluate the socioeconomic aspects of understory cleaning or other intervention measures such as vineyard cultivation to reduce the spread of wildfires and increase avoided CO_2 emissions. The fourth chapter assesses the socio-economic aspects of measures as a consequence of changes in the balance of the water cycle. Since the methodology used is different for each approach, it is explicit within each of the three chapters. Finally, the fifth chapter summarizes the main conclusions of the evaluation carried out.

2. Evaluation of adaptation measures – fire risk and population fixation

Evaluation is the action of analyzing a certain policy, program or public intervention to answer a question related to the problem that the program tries to solve. Through evaluations, the public decision-maker can have greater knowledge about the different aspects of public policy and, consequently, must be able to improve this policy.

As for forestry policies, and to partially reverse the trend of forest advance (afforestation) in the Iberian Peninsula and, by extension, in southern Europe, clearings are configured as an opportunity to partially restore cultural landscapes, recover traditional extensive livestock, emphasize the complexity historically introduced by human activity, and help improve biodiversity and runoff production (blue water) without increasing the risk of soil erosion. The purpose of these actions is to build a more complex and heterogeneous landscape, recover part of the cultural landscape, increase biodiversity, reduce the probability of large wildfires, increase the provision of ecosystem services and improve the survival of extensive livestock systems that also contribute to biodiversity (García-Ruiz et al., 2020).

La Rioja is one of the communities that has been a pioneer in forest management of clearings (Lasanta et al., 2022). These clearings combine mechanical bush cleaning with cattle grazing. The objectives are like those pursued with the prescribed burns: reduce biomass and create a mosaic landscape, with forests alternating with shrub and pasture areas. Thus, in addition to these two main objectives, it is also possible to reduce the prescribed biomass burns, the origin of possible wildfires due to accident or negligence. The objective is to manage the land for environmental purposes (fire reduction) and socioeconomic (promoting extensive livestock and fixing the population in the territory).

In 1986 the government of La Rioja launched a shrub clearing plan to improve fire control and promote extensive livestock farming (Lasanta et al., 2022). Since then and until 2020, 28.4% of the shrub area has been cleared, which has contributed to creating a more fragmented and diverse landscape. This has meant the reduction of the total burned area from an average of 1,060 ha per year between 1968 and 1986 to an average of 221.7 ha per year between 1987 and 2020.

This clearing plan has never been applied in the provinces of Burgos and Soria, in the autonomous community of Castilla y León, as they are different autonomous communities. In Castilla y León the clearing policy has not been much less intense neither in treated area, nor in economic endowment. One of the actions that was carried out is the so-called Plan 42. This plan was intended for the 42 municipalities of Castilla y León (1.9% of the total) in which 40% of the wildfires of the community occurred. Each of these municipalities had suffered, in the five-year period 1995-1999, a minimum of 50 wildfires and a maximum of 243 (Molinero, F.; Garcia, A.; Cascos, C.; Baraja, E.; Guerra, 2008). Thus, the total number of wildfires generated in this five-year period in the 42 municipalities was 3,862. This Plan 42 was only in force between 2002 and 2010, a period during which positive results were achieved in terms of forest fire prevention, which were reduced in number in certain areas of the Autonomous Community. This Prevention Plan ceased to be operational in 2010 due to the lack of public funds, to which was added the lack of qualified personnel, lack of tools and advice to the municipalities. The nearest area of action was the north of the province of Burgos, about 50 km from the border between the two autonomous communities.

The main objective of this chapter is to quantify the effect of clearing in the reduction of wildfires in the mid-mountain, as well as the economic savings in extinguishing wildfires and the economic losses derived from these wildfires. Also, population variations in areas with clearing will be analyzed, comparing their effects with areas where they have not occurred.

The indicators to be used shall meet the criteria of credibility, legitimacy, relevance and replicability.

2.1. Methodology and data

2.1.1. Study area

The study area is comprised of two parts: the treated and the control zone. The treated zone corresponds to the mid-mountain of La Rioja. We understand as mid-mountain those areas with an altitude between 700 and 1,500 m. This means that, from this community, a part with altitudes higher than 1,500 m and that borders the province of Soria is excluded, as well as the Ebro river valley because it has an altitude of less than 700 m, located in north of this community crossing it from west to east (Figure 1).

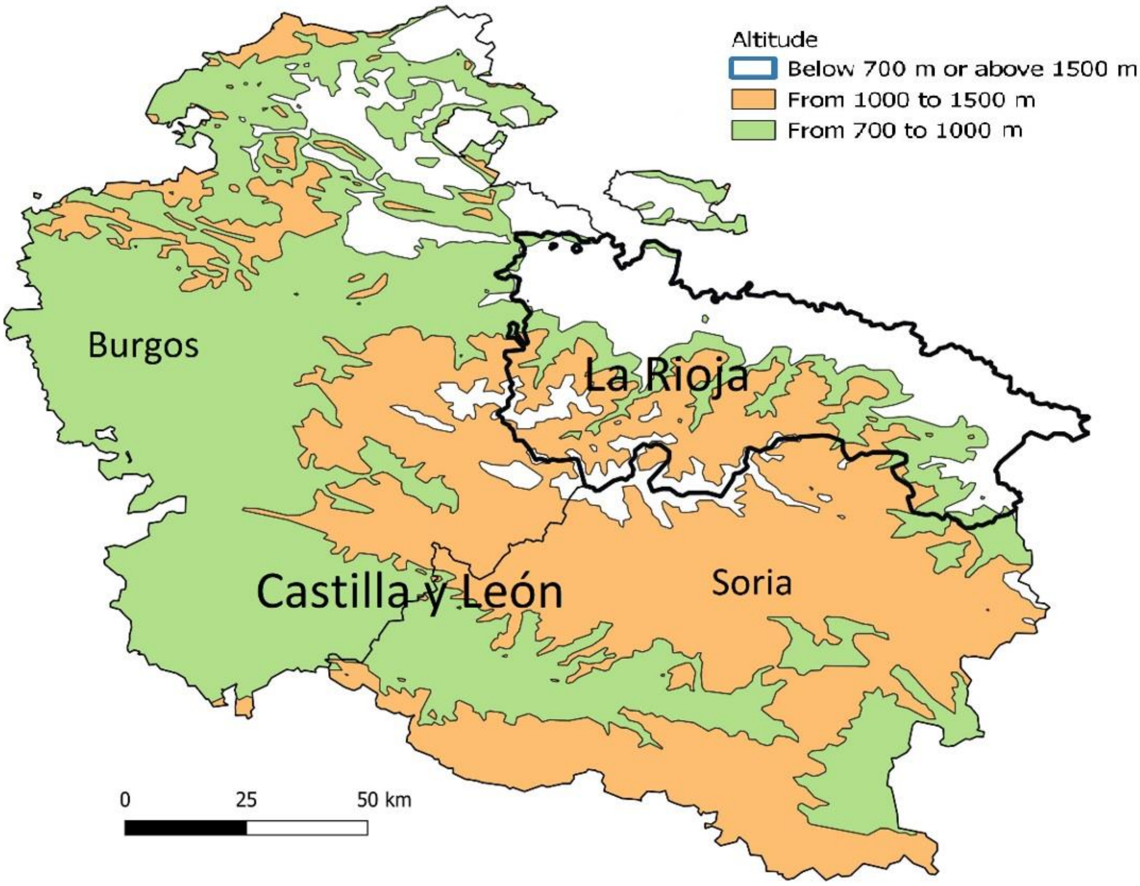

Figure 1. Study area setting according to altitude

The control area corresponds to the mid mountain bordering la Rioja mid mountain. In this case, in the provinces of Burgos and Soria, in Castilla y León, which are bordering in the mid mountain of La Rioja. The same altitude range criterion (between 700 and 1500 m) applies. With regard to the province of Soria, practically all this province becomes a control zone. With regard to the province of Burgos, a part of the northwest is mostly excluded due to an altitude lower than that chosen, but also a good part of this province becomes a control zone (Table

Province	Total area (km^2)	Study area (km^2)	Percentage study area over total area (%)
La Rioja	5,045	2,888.6	57.26%
Burgos	14,292	12,873	90.07%
Soria	10,306	9,986	96.90%

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Table 1. Total area and study area by province

An important limitation emerges from the previous study area: areas with a distance greater than a hundred kilometers from the boundary between the treated and control area are being compared. Although these factors are taken into account, a starting study area with more similar characteristics can facilitate comparison. Thus, maintaining the altitude criterion explained in Figure 1,Figure 1Figure 2). This buffer is intended to reduce the effect of other variables as they are different geographical scenarios. To limit the randomness in the generation of this buffer, it is decided to perform a first buffer of 10 km radius.

In Figure 2 it is represented within the buffer area, as the gray area. It represents approximately 10 km from the administrative boundary between the two communities to a point in the treated area or control furthest from this border. With this buffer, the main problem is that the number of wildfires is very low and does not allow the comparison between both areas with total guarantees that there are enough observations. Thus, a buffer of 20 km radius is chosen (red and green dots in Figure 2).

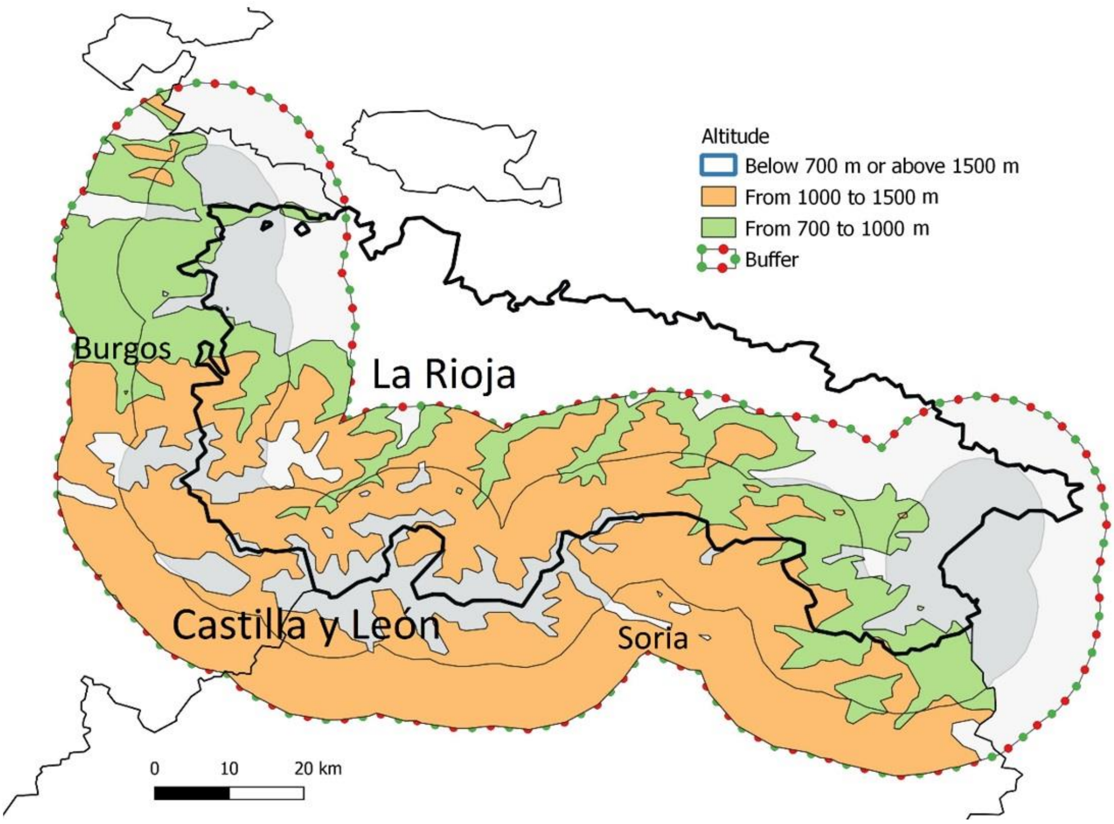

Figure 2. Definition of the study area according to altitude and a buffer of 20 km radius

Area	Altitude	La Rioja (km^2)	Burgos (km^2)	Soria (km^2)	Total (km^2)
Buffer	700-1.000 m	829	649.8	184.9	1,663.7
	1.000-1.500 m	1,266.7	740.9	1,898.4	3,906
Total		2,095.7	1,390.7	2,083.3	5,569.7

Table 2FigureFigure 2. Compared to the data in

Province	Total area (km^2)	Study area (km^2)	Percentage study area over total area (%)
La Rioja	5,045	2,888.6	57.26%
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Table 1, there is a large reduction in the area susceptible to study in the provinces of Burgos and Soria. Thus, the buffer that corresponds to an approximate radius of about 20 km implies that 37.63% of the total surface corresponds to La Rioja, while 62.37% in Castilla y León.

Area	Altitude	La Rioja (km^2)	Burgos (km^2)	Soria (km^2)	Total (km^2)
Buffer	700-1.000 m	829	649.8	184.9	1,663.7
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Table 2. The study area by buffer and provinces

The forest fire database has been developed by the NGO Civio based on forest fire data available to the Ministry of Agriculture, Fisheries and Food (MAPA). There is no database in Spain as wide and with as many variables as this one, and that presents geographical homogeneity in its elaboration. As the main limitation, it only includes wildfires between 2001 and 2015. Thus, it has been preferred to have the most faithful database of reality, although the time period is not the most recent.

There are other minor limitations such as:

- The causality of wildfires is not certain but assumed in more than 55% of cases.
- The geolocation of wildfires is not specified in almost 18% of them.
- Information on economic losses and expenses is very scarce, which makes it very difficult to analyze the real cost of the fires that have occurred. More than 30% of fire reports do not provide extinguishing expense data and almost 9% lack economic loss data.
- Data provided by the Ministry may contain errors.

For each forest fire, the following variables are available, among others:

- Fire detection date.
- Fire start geographical coordinates, as well as the autonomous community, province and municipality.
- Fire cause.
- Burned area.
- Number of deaths.
- Number of injured.
- Time to have the fire under control.
- Time to extinguish the fire.
- Number of people who have participated in extinguishing the fire (includes technicians, forest agents, brigades, firefighters, volunteers, civil guards and army).
- Number of ground and air assets involved in extinguishing the fire (including car bombs, bulldozers, tractors, aircraft and others).
- Extinguishing costs associated with the fire.
- Economic losses associated with the fire.

2.1.2. Geographic Information Systems

The layers in a Geographic Information System (GIS) have a large amount of information, a fact that should be considered as a database. From the National Geographic Institute, the following are used:

- Boundaries of autonomous, provincial and municipal communities. From these layers, both the municipal term and buffer area for the treated and control areas will be calculated.
- Orography: to choose the territory considered as mid mountain, the surface that has an altitude between 700 and 1,500 m above sea level will be chosen, differentiating between 700 and 1,000 m and between 1,000 and 1,500 m. For each municipality, the altitude of this will also be chosen.
    - Land covers from the European project CORINE Land Cover with a nomenclature of forty-four classes and with 1990 version. The predominant type of land cover in the municipality is chosen. A classification of four types of vegetation covers is made: rainfed crops, forest, shrub and vineyards. Within the forest category, hardwood, coniferous and mixed forest are included. As for shrub, the category of natural pastures, moors and shrub, sclerophyllous vegetation and transitional forest shrub is included.

2.1.3. Census

As for the municipal population, census data conducted by the Spanish National Institute of Statistics in 1999, 2009 and 2020 are taken. Also, the data of the municipal register for the year 2015, which coincides with the end of the period of the forest fire data. As for the agricultural censuses, these are carried out according to the calendar established by the European authorities. Thus, the agrarian censuses of 1999, 2009 and 2020 are chosen to obtain the information at the municipal level. The variables chosen are the number of heads of sheep and goats, since they are the herds that benefit most from shrub clearing. The 2020 census is also used for descriptive purposes.

2.1.4. Model

This evaluation aims to answer the question of whether a clearing policy has an effect in reducing the number of fires or not in the mid mountain. The study area, as already mentioned, corresponds to the area of the mid mountain between La Rioja and Castilla y León created from a buffer of 20 km.

To isolate the effect of clearings, it is proposed to use a set of linear regressions that allow to isolate the effect of these clearings controlling for different variables. Thus, a logistic regression model is proposed with the following explanatory variables:

$$Any\ wildfire_i = La\ Rioja_i + Surface_i + Altitude_i + Vegetation_i + Population\ (\log)_i + \text{Population density}_i + \text{Sheep and goats density}_i + \varepsilon_i$$

- The dependent variable *Any wildfire* is a dichotomous variable that takes the value 1 if in that municipality of the buffer there has been a wildfire between 2001 and 2015, and zero otherwise. Thus, in this model there is not a temporal effect of the clearings to be observed.
- *La Rioja* variable is a dichotomous variable that takes the value 1 if that municipality is in La Rioja, while it takes the value zero if it is in Castilla y León.
- *Area* variable are the km^2 of the municipality.
- The *Altitude* variable is the altitude above the sea in which the City Council of that municipality is located.
- The *Vegetation* variable is a categorical variable that can take four possible values: crops, forest, shrubs and vineyards.
- The *Population* variable It is the logarithm of the population in that municipality in 2015.
- *Population density* variable are the inhabitants per square kilometer in that municipality in 2015.
- *Sheep and goats density* variable is the number of cattle per square kilometer of the municipality in 2009.

In this model you can change the definition of the dependent variable from "if there has been a fire in that municipality" to "if there has been a fire in that municipality due to a specific cause". That is, since wildfires can be caused by lightning, intentional causes, accidents, negligence, or unknown causes. These four variables can also be dependent variables in different regressions.

2.2. Results

2.2.1. Wildfires descriptive analysis

In Figure 3 wildfires between 2001 and 2015 are represented. As can be seen, a lower number of wildfires are detected in La Rioja, especially in the area between 1,000 and 1,500 m. A relatively homogeneous distribution of wildfires is detected throughout the mid-mountain area of Castilla y León, but with the exception of the La Rioja area, where there are areas with practically no wildfires.

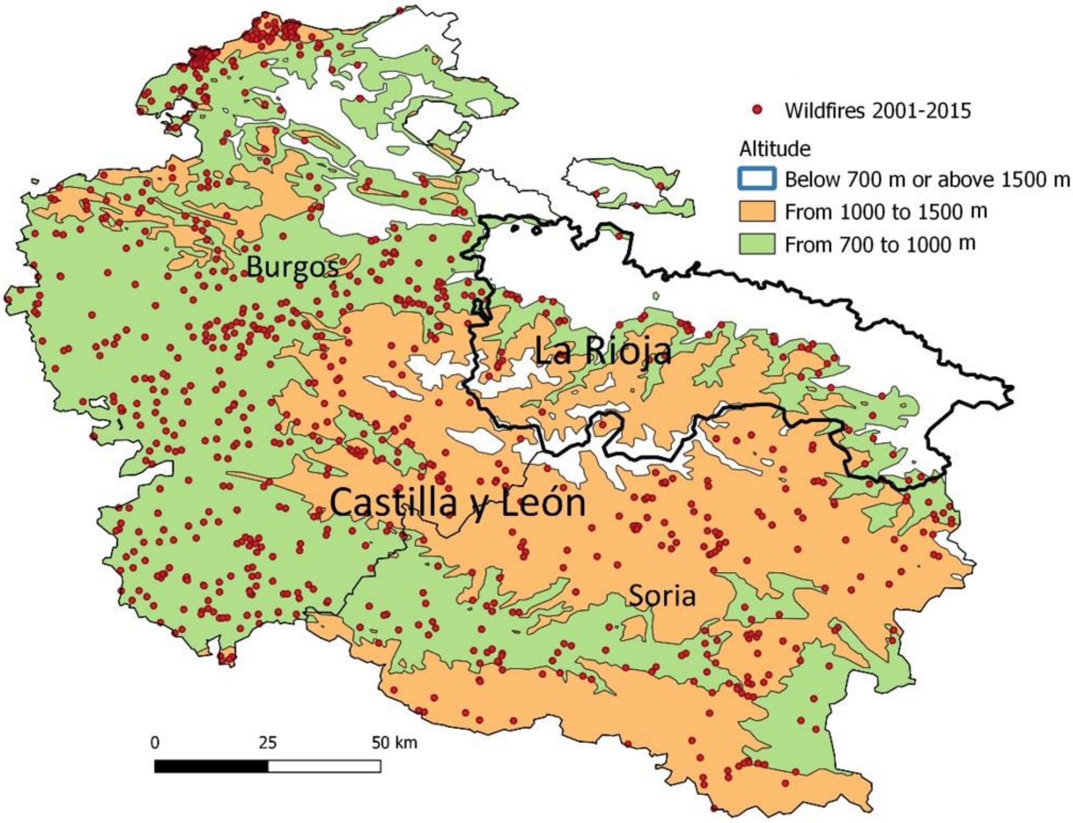

Figure 3. Wildfires in the study area between 2001 and 2015

Continuing with the same argument of the importance of reducing the number of fires for the same surface unit, in Figure 4 it is shown the evolution over time of the number of wildfires per 1000 km^2 is shown. As can be seen, the decreasing trend in both areas is very similar, although it is noteworthy that the number of fires has decreased more in La Rioja than in Castilla y León.

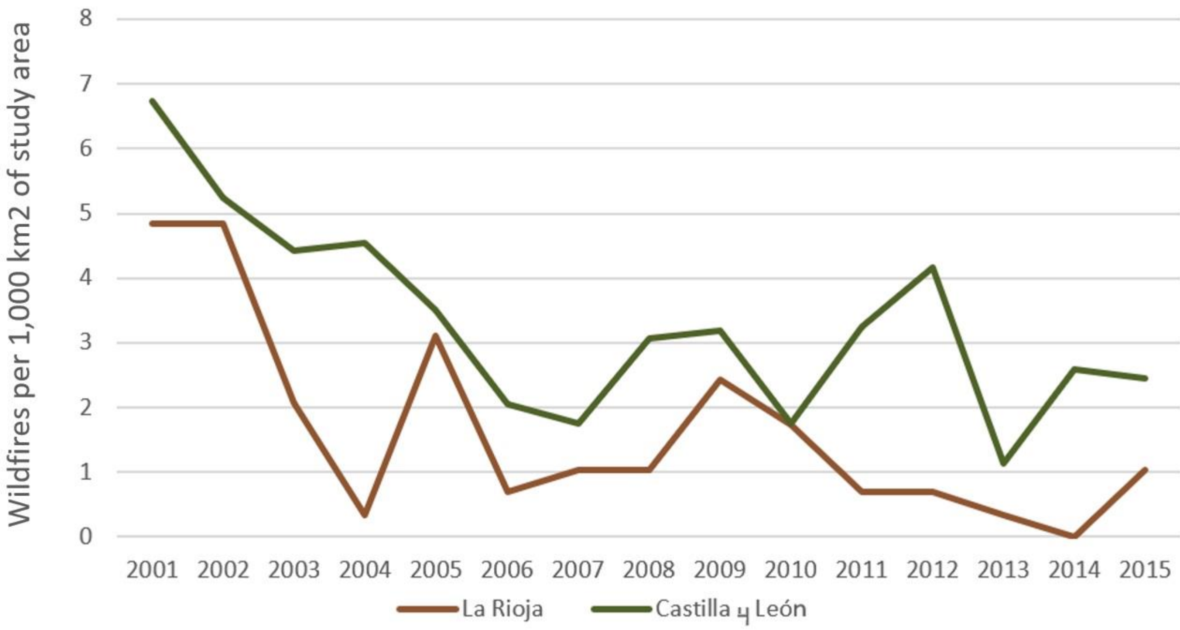

Figure 4. Temporal evolution of the number of fires by surface area in the autonomous communities of La Rioja and Castilla y León

2.2.2. Descriptive analysis of the buffer or influence area

In the previous subsection, the main results have been described when the study area corresponded to the entire surface of the provinces of the study area that were in the selected altitude range (Figure 1). Next, the descriptive analysis will be performed when the selected area corresponds to a buffer of 20 km radius (Figure 2).

Figure 5 shows wildfires between 2001 and 2015. At first glance you can see how in La Rioja the number of wildfires is lower. More specifically, at an altitude between 1,000 and 1,500 m, the difference with Castilla y León is clear. As regards the height between 700 and 1,000 m, this difference does not seem so clear. If we look at whether a fire has been declared in a municipality in this period in the different autonomous communities, we find that, in Castilla y León, 49.25% of the municipalities have had at least one fire while for La Rioja, only in 22.4% of the municipalities there has been at least one fire. A mean test tells us that these values are different for a significance level of 99%. Therefore, it is confirmed that there are differences in whether a municipality has suffered a fire or not during this period depending on the autonomous community to which it belongs.

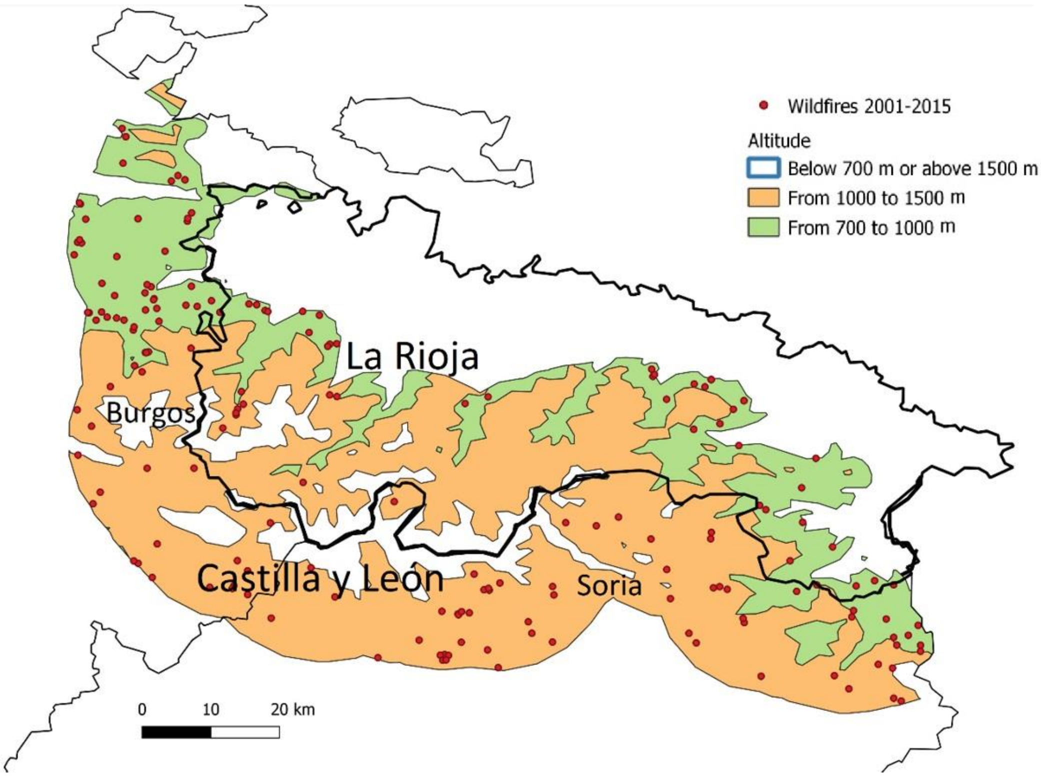

Figure 5. Wildfires in the buffer study area between 2001 and 2015

Figure 6 shows the four main causes of starting a fire: by lightning, by intentional cause, by accident or negligence and by unknown cause.

- As for lightning, in La Rioja there are two wildfires while in Castilla y León six. With these values, a mean difference test tells us that these two values do not present differences for both groups.
- As for intentional fires, a greater number of fires are detected in Castilla y León than in La Rioja. More specifically, 28.4% of the municipalities of Castilla y León had at least one fire due to intentional cause, while, in La Rioja, it stands at 20.7%.
- On the other hand, when the cause of origin of the wildfire is an accident or negligence, Figure Figure 6 shows that in La Rioja there is only one fire. Thus, in 6.7% of the municipalities of Castilla y León there has been at least one fire due to accident or negligence while in La Rioja it has only been 0.9%. For a significance level of 95%, these values are different.

- As for wildfires of unknown cause, these occur in 5.2% of the municipalities of Castilla y León and in 2.6% of the municipalities of La Rioja.

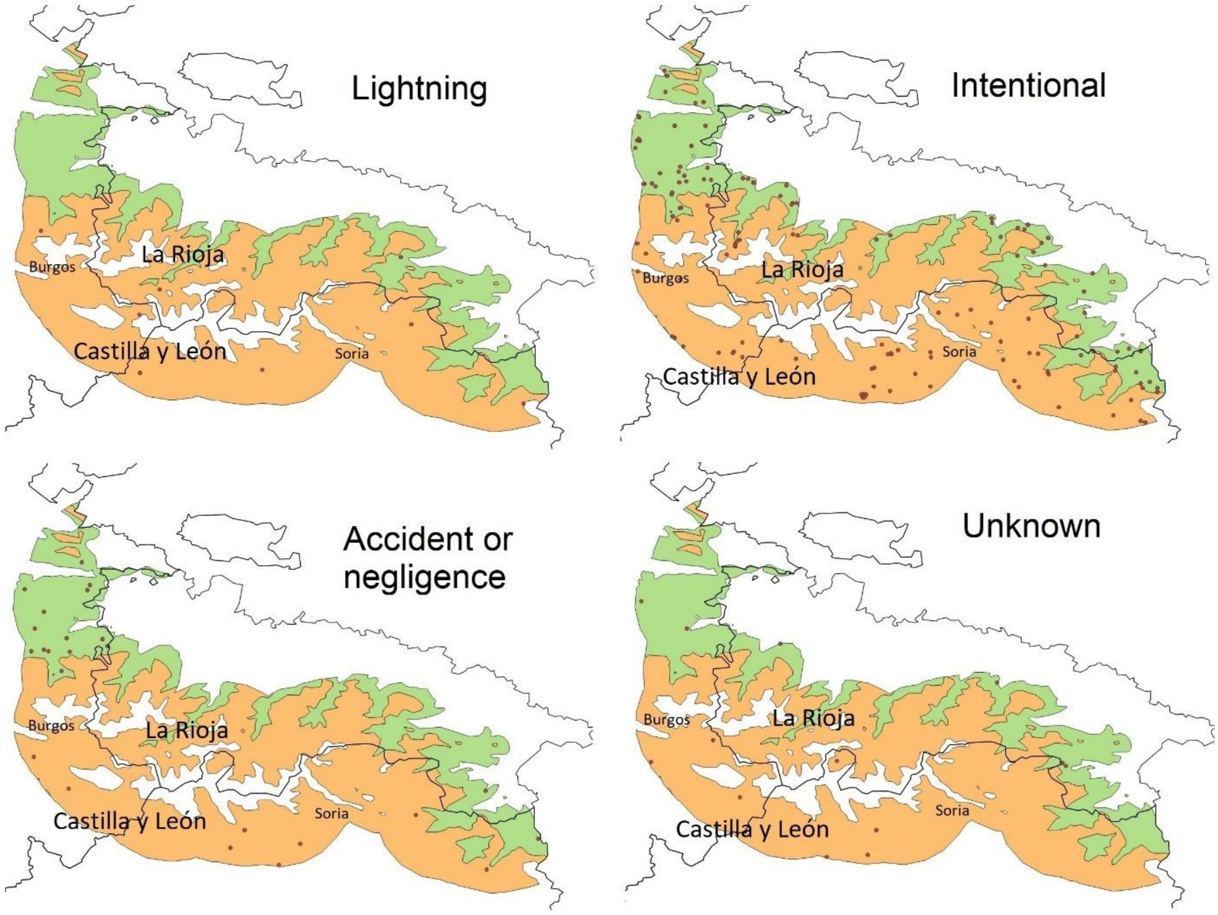

Figure 6 . Distribution of fires by type of cause of the onset

	Number of wildfires		**Number of wildfires per 1.000 km²**	
	Castilla y León	La Rioja	Castilla y León	La Rioja
Lightning	6**	2	1,73	0,95
Intentional	97**	47	27,92	22,43
Accident or negligence	23	1	6,62	0,48
Unknown	4*	8	1,15	3,82
Total	134**	54	38,57	25,77

Significance levels: * 90%, ** 95%, *** 99%

Table 3. Distribution of wildfires by initial cause

Significance levels: * 90%, ** 95%, *** 99%

Table 3 shows the number of fires in each autonomous community of the buffer and according to the cause of origin. As for lightning, the proportion is 6 fires in Castilla y León and 2 fires in La Rioja, this difference being significant to 95%. However, if we do it by buffer surface, this difference is reduced. As for intentional fires, we find twice as many fires in the area of Castilla y León as in La Rioja. These averages are statistically different from each other. However, when we correct for buffer area, the number of fires due to intentional cause in Castilla y León is still 24.5% higher than in La Rioja.

When the cause is an accident or negligence, the proportion is 23 fires in Castilla y León and 1 in La Rioja. It is not possible to perform a mean difference test since there is only one observation on the La Rioja side. However, the proportion of fires due to accident or negligence is much higher in Castilla y León. If we do it by buffer surface, we find that in Castilla y León there are 13 times more fires due to accident or negligence than in La Rioja. Therefore, there is sufficient evidence that fires due to accident or negligence occur in fewer numbers in La Rioja. As for fires for unknown causes, we find that there are more in La Rioja, both in absolute figures and relative to the surface.

From this data, we can confirm that in the area of the Riojan buffer there have been many fewer wildfires due to accident or negligence than on the side of the buffer of Castilla y León. Likewise, the number of fires due to intentional causes are also much lower in La Rioja than in Castilla y León.

As for the characteristics of wildfires, we find that 1,449 ha have been burned in the area of Castilla y León, and 917 ha in La Rioja. If we look at the area burned by all the fires during the analysis period by buffer area, in La Rioja the fires that have occurred have burned 0.437 hectares per square kilometer of buffer (Table 4), while in Castilla y León the figure is slightly lower. Thus, the greater number of fires in Castilla y León than in La Rioja would be accompanied by a much larger area burned by fire in Castilla y León (16.97) than in the part of the Rioja buffer (10.81).

Study area	Area	Burned ha	Ha burned / buffer km^2	Burned ha per wildfire
Buffer	La Rioja	916,6	0,437	10,81
	Castilla y León	1.449,2	0,417	16,97

Table 4. Relative burned area within buffer

2.2.3. Descriptive analysis of livestock and population

Next, the evolution of cattle heads and the population in the buffer is compared. Regarding the density of sheep and goats, in 1999 they were very similar between the two autonomous communities (Figure 7). Over time, there is a decrease in the number of heads in both areas, with the difference that in Castilla y León this decrease is greater than in La Rioja, whether we choose 2009 or 2020. Thus, the decrease in the absolute number of sheep and goats, is lower in La Rioja (Figure 8). In terms of population density, it is much higher in La Rioja than in Castilla y León. Thus, we see that between 1999 and 2009 the population density increased by 8% in Castilla y León, while in La Rioja it did so by 16% (Figure 8).

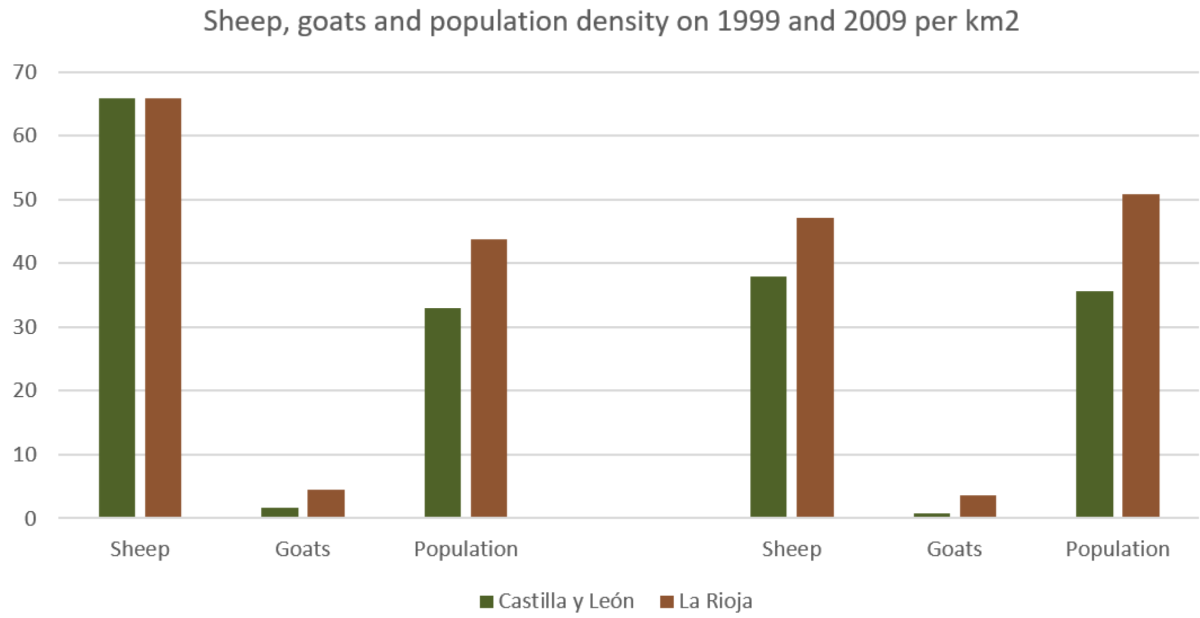

Figure 7. Temporal evolution of cattle density and population in the buffer

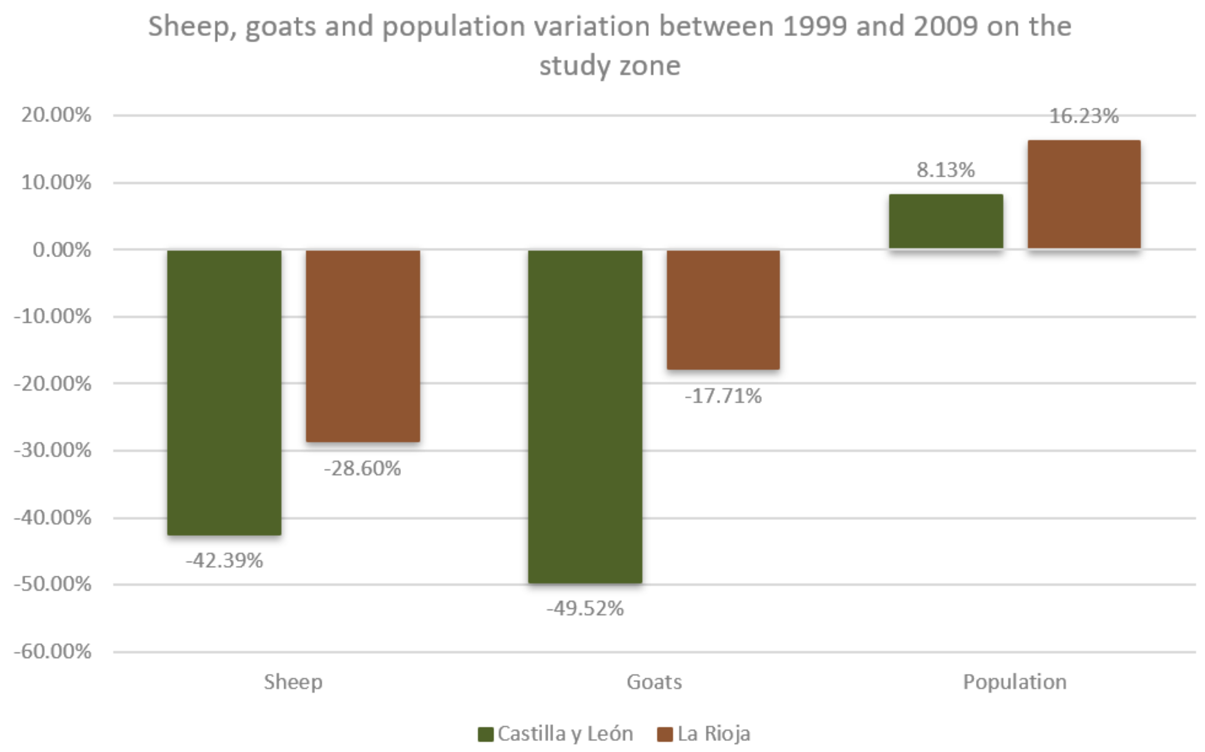

Figure 8. Change in the number of sheep, goats and population in the buffer between 1999 and 2009

Although the decrease in cattle is more pronounced in the part of Castilla y León than in La Rioja, some differentiated territorial dynamics could be detected in the buffer. Therefore, Figure 9 compares the evolution of cattle (sheep and goats) between 1999 and 2020. As can be seen, there is no very marked geographical dynamic between the different bands of the border. However, it is observed that there are more municipalities in the Rioja area that increase the number of cattle by more than 25% than in the area of Castilla y León. On the other hand, strong reductions in cattle occur more frequently in Castilla y León than in La Rioja. Thus, a certain spatial dynamic of decreases of cattle is detected where shrub clearing and / or thinning have not been done.

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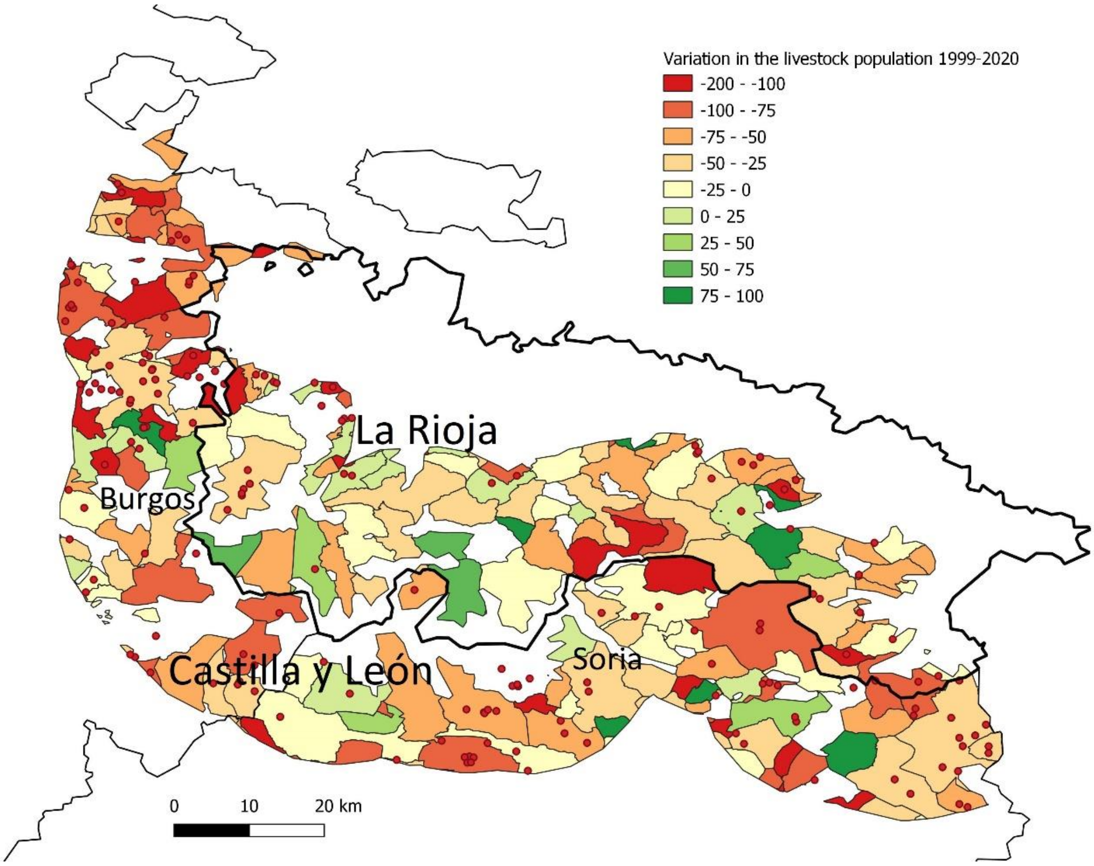


Figure 9. Variation of sheep and goats between 1999 and 2020 by municipality

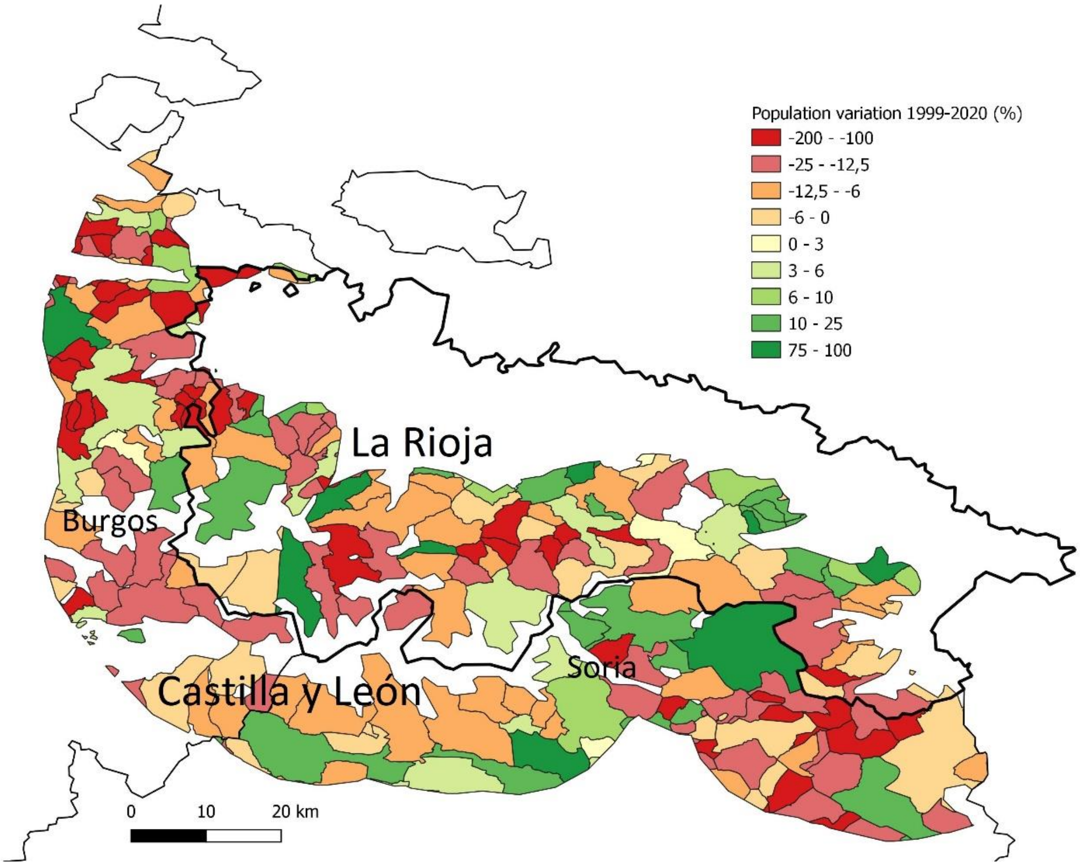


Figure 10. Change in population density between 1999 and 2020 by municipality.

To complement Figure 9Figure 10, Figure 10Table 5). For each year, we perform a mean difference test between both values. As for cattle, in 1999 there was more density of cattle in Castilla y León than in La Rioja. Over time, that difference disappears. Although the figures may indicate that in La Rioja there is a density of cattle 50% higher than in Castilla y León (30.23 vs 20.80), this cannot be confirmed since the mean difference test tells us that this difference is not significant for the year 2020. In terms of population density, in 1999 there was no significant difference between the two areas. However, the population density in Castilla y León is lower than in La Rioja overtime. Thus, we would be facing a dynamic of population decreasing in the Castilian area.

	Density of sheep and goats (heads/km^2)			Population density (inhabitants/km^2)		
	1999	2009	2020	1999	2009	2020
Castilla y León	61.90***	28.42	20.80	12.26	12.06*	10.51*
La Rioja	41.78	35.23	30.23	18.31	21.15	19.45

Significance levels: * 90%, ** 95%, *** 99%

Table 5. Mean number of cattle and inhabitants by municipalities and years of censuses in the buffer area

Among the different variables, we can look at what their level of relationship is. Therefore, Table 6 shows the level of pairwise correlation for the municipalities that are within the analysis buffer. The value of that correlation, its level of significance and the number of observations are displayed. For the variables related to the number of sheep, goats and their total, the 2009 census is taken. If we had taken the data from the 2020 census, there is no change in the levels of significance found and described below. The number of inhabitants in a municipality has a positive relationship with the fact that there has been a fire in the municipality, although with a correlation value between low and moderate. Other variables to highlight that do not seem to affect the occurrence of a fire is the density of sheep, goats or the sum of heads in total. Not too many differences are detected between La Rioja and Castilla y León with the variables analyzed. It is only detected that in La Rioja there is a higher density of goats. However, this result is not transferable for sheep. The coefficient between the dichotomous variables *La Rioja* and *Any wildfire* sometimes does not make much sense to interpret, although it shows a moderate and negative level of relationship between having produced a fire in a municipality and that this municipality is not in La Rioja. This value seems to confirm the values of Figure 5, where in La Rioja there are fewer wildfires than in Castilla y León.

	Any wildfire	La Rioja	Population (log)	Population density	Sheep density	Goats density	Cattle density
La Rioja	-0.300	1					
	0						
	250	250					
Population (log)	**0.179**	0.030	1				
	0.005	0.634					
	250	250	250				
Population density	-0.050	0.066	0.661	1			
	0.433	0.298	0				
	250	250	250	250			
Sheep density	0.034	0.077	0.053	0.070	1		
	0.625	0.262	0.441	0.308			
	214	214	214	214	214		
Goats density	-0.006	**0.287**	0.050	0.019	0.295	1	
	0.936	0	0.485	0.793	0		
	200	200	200	200	194	200	
Cattle density	-0.049	0.041	-0.105	-0.003	0.817	0.310	1
	0.471	0.544	0.119	0.965	0	0	
	220	220	220	220	214	200	220

Table 6. Pairwise correlation in the buffer zone with the level of significance and number of observations

We describe the differences between the buffer areas that have had at least one fire or none and by autonomous communities. With this comparison, it is intended to make an approximation to the regressions of the following subsection. First, in 49.25% of the municipalities of Castilla y León there has been at least one fire between 2001 and 2015, while in La Rioja it has only occurred in 22.4% of the municipalities (Significance levels: * 90%, ** 95%, *** 99%

Table 5). A mean difference test indicates that this result is statistically significant at 99%. Therefore, there is more than twice the probability of finding a municipality with at least one forest fire in the area of Castilla y León than in La Rioja.

Despite this probability, there may be differences on different variables between autonomous communities. For example, the municipalities of Castilla y León that have suffered a fire have an area of 51.6 km^2, while the municipalities of the Rioja that have suffered a wilfire have an area of 46.9 km^2. Despite this difference, these are not statistically significant. As for the altitude, the municipalities of Castilla y León where there has been a wildfire, it has been declared at 987.5 m while in La Rioja at 722.4 m. The mean difference is statistically significant at 99%. Also, the municipalities where no fire has been declared in Castilla y León, have an altitude above sea level of 947.7 m, while, in the municipalities of La Rioja without any fire, it is 754.3 m. This mean difference is statistically significant at 99%. As for the other variables, no difference is detected between the occurrence of wildfires in one or another autonomous community. Only that in the municipalities of Castilla y León where there have been no wildfires, the density of heads is lower than in La Rioja (16.1 vs. 30.7). On the other hand, there is no statistically significant difference in the density of cattle in Castilla y León between the municipalities where there has been at least one fire and where there has never been any fire.

	Castilla y León		La Rioja	
	At least one wildfire	No wildfire	At least one wildfire	No wildfire
Proportion of municipalities with at least one wildfire (%)	49.25***	50.18	22.4	77.6
Surface (km^2)	51.56	28.32	46.93	30.57
Altitude (m)	987.47***	947.72***	722.35	754.29
Crops (%)	22.73	44.11	19.23	30.00
Shrubland (%)	19.70	11.77	34.62	22.22
Forest (%)	57.57	44.12	42.31	43.33
Vineyard (%)	0	0	3.84	4.45
Population (hab.)	1058.06	653.18	908.6	784.42
Population density (hab/km^2)	10.40	10.61	15.87	20.48
Cattle density (heads of cattle/km^2)	25.68	16.06**	28.83	30.65
Observations	134		116	

Significance levels: * 10%, ** 5%, *** 1%

Table 7. Different variables mean by municipalities with and without a fire and by autonomous community

2.2.4. Economic analysis of wildfires in the buffer or area of influence

In this subsection, it is intended to analyze whether there are differences in extinction expenses and losses linked to wildfires. As described in section 2.1.2, economic information is not provided for most fires. Thus, for the variable extinguishing expenses and losses linked to these fires, few observations are available. More specifically, for the total of 188 fires in the buffer, data are only available on extinguishing costs for 72 fires, and on losses caused by these in 75 fires. On the other hand, the economic values are updated according to the inflation data for Castilla y León and La Rioja, with the figures in euros corresponding to 2021.

Table 8 shows the extinguishing costs and losses caused by wildfires for each autonomous community according to the buffer area. The extinction costs in La Rioja are € 917.67 per hectare, while in Castilla y León they are € 1,292.87. Although in Castilla y León they are higher, a mean difference test does not allow us to affirm that both values are different. On the other hand, in losses per hectare burned we do find significant differences. That is, the losses in the Rioja area are € 237.57 per hectare, while in Castilla y León they are € 1,274.03. The difference in losses caused is € 1,036.56, while in extinguishing expenses it is € 375.02. Thus, the difference in extinction expenses and losses would be € 1,411.58 per hectare burned.

Study area	Area	Wildfire extinction expenses / ha burned	Wildfire losses / ha burned
Buffer	La Rioja	917.67 €	237.57** €
	Castilla y León	1,292.87 €	1,274.03 €

Significance levels: * 10%, ** 5%, *** 1%

Table 8. Extinguishing costs and losses per hectare burned

This magnitude of € 1,411.58 corresponds to the differential of direct costs caused by wildfires in the buffer area of Castilla y León compared to La Rioja.

2.2.5. Regressions

Table 9 shows the results of the regression described in the Methodology subsection. The main objective is to analyze if there are effects of *La Rioja* variable, so explanatory variables are added to find if there is any change in the behavior of this variable on whether there has been a forest fire. First of all, we must say that the variables used in each of the specifications add predictive value, as shown by the likelihood ratio test. On the other hand, the variability explained by the explanatory variables is increasing as we add more variables. Thus, the R^2 McFadden goes from a value of 0.074 to 0.175. However, it is worth noting the value of this statistic when only the dichotomous variable *La Rioja* is included, which explains 0.074 of the total variability of the dependent variable. Thus, being in one or another geographical area seems to have some explanatory power. Another statistic in the model corresponds to the value of the Akaike (AIC). The specification to choose will be the one with the lowest value. In our case, the specification with the most variables included (specification 5) would be the specification to choose. On the other hand, a multicollinearity test of inflation factor of variance has been carried out and all variables are below four, which allows us to rule out the presence of multicollinearity.

The dummy variable *La Rioja* is negative and significant for all specifications. If we interpret this coefficient on odds ratio of logistic regression, we find that in La Rioja municipalities there is between 67 and 77% less probability that there was at least one fire between 2001 and 2015 compared to the border area of the buffer of Castilla y León.

Next, we explain the results of the explanatory and control variables. The variable *Surface* is positive and significant; the larger the area of the municipality, the greater the probability of suffering a fire between 2001 and 2015. The *Altitude* variable is not significant for any of the specifications. The categorical variable type of vegetation does not seem to affect the probability of at least one fire in that municipality, broadly speaking. However, the variable *Shrub* is significant in most specifications: when the predominant vegetation is shrub, there is between 2.4 and 2.6 more likely that a fire has occurred in the municipality.

Population in a municipality is positive and 99% significant for both specifications; the larger the population of a municipality, the greater the probability that a fire has occurred. As far as population *density* is concerned, it is negative and significant. Thus, municipalities with higher population density are less likely to have suffered a wildfire. As for the *density of sheep and goats*, this variable does not affect whether to have a wildfire or not.

Dependent variable: any wildfire between 2001 and 2015	**Spec. 1**	**Spec. 2**	**Spec. 3**	**Spec. 4**	**Spec. 5**
	Coef. (Error. St.)	**Coef. (Error. St.)**	**Coef. (Error. St.)**	**Coef. (Error. St.)**	**Coef. (Error. St.)**
La Rioja	-1.202*** (0.263)	-1.107*** (0.298)	-1.385*** (0.337)	-1.371*** (0.340)	-1.471*** (0.385)
Surface		0.015*** (0.004)	0.014*** (0.005)	0.005 (0.006)	0.021*** (0.006)
Altitude (log)		0.406 (0.543)	-0.413 (0.707)	-0.226 (0.809)	0.239 (0.843)
Type of vegetation (crops)					
Shrubland			1.182** (0.478)	1.064* (0.484)	0.836 (0.511)
Forest			0.502 (0.425)	0.242 (0.440)	0.066 (0.466)
Vineyard			-0.941 (1.384)	-0.915 (1.390)	-1.161 (1.432)

Dependent variable: any wildfire between 2001 and 2015	Spec. 1	Spec. 2	Spec. 3	Spec. 4	Spec. 5
Population (log)				0.559*** (0.192)	0.631*** (0.210)
Population density				-0.014** (0.007)	-0.016*** (0.007)
Sheeps and goats density					0.009 (0.040)
Constant	0.002 (0.171)	-3.340 (3.720)	1.845 (4.714)	-4.565 (5.722)	-4.858 (5.948)
Observations	250	250	250	250	250
R^2 McFadden	0.074	0.122	0.144	0.174	0.175
Likelihood-ratio test (p-valor)	24.28 (0.0)	40.22 (0.0)	47.46 (0.0)	57.12 (0.0)	51.62 (0.0)
AIC	308.66	296.72	295.49	289.89	262.80

Table 9. Logistic regression (odds-ratio) on any wildfire in municipality in the buffer between 2001 and 2015

As described in the Methodology subsection, the dependent variable can be a dummy variable that takes the value 1 if there has been a wildfire for a specific cause and 0 for any other reason. TableTable 10TableTable 9, as it is the preferred specification because it has the lowest value of the Akaike criterion (AIC). Regarding the specification of fires caused by lightning, *La Rioja* is not significant; There are no territorial effects on lightning fires. As for intentional fires, a negative effect is detected in the area of the Rioja buffer. This negative and highly significant coefficient has an interpretation of a 74% reduction in the probability that at least one fire was declared between 2001 and 2015 in the area of the Rioja buffer, keeping all other variables the same. When the cause of the fire is unknown, no significant effect on *La Rioja* variable is detected either. Regarding the specification of wildfires caused by negligence or accident, the variable *La Rioja* is not significant. In Table 10**Error! Reference source not found.** you can see how fires due to negligence are practically non-existent in La Rioja, while the model does not find any significant effect, although the coefficient appears with a negative sign. In the number of observations, it is seen that about fifty-five observations have been lost in the regression, which may explain this result. These observations are lost due to multicollinearity of the vegetation type variable.

Dependent variable	Lightning	Intentional	Negligence	Unknown
	Coef. (Error. St.)	Coef. (Error. St.)	Coef. (Error. St.)	Coef. (Error. St.)
La Rioja	-0.910 (1.239)	-1.338*** (0.412)	-1.869 (1.188)	-0.819 (0.821)
Surface	0.020 (0.017)	0.003*** (0.006)	0.001 (0.011)	-0.003 (0.013)
Altitude (log)	4.088 (3.596)	-2.947 (0.898)	-0.656 (1.880)	-1.205 (1.670)
Type of vegetation (crops)				
Shrubland	-	0.975* (0.516)	-	-
Forest	-9.848** (4.529)	0.727 (0.474)	-1.044 (0.958)	0.491 (0.948)
Vineyard	-	-1.252 (1.177)	-0.941 (1.384)	-
Population (log)	-0.991 (0.793)	0.203 (0.197)	0.442 (0.380)	0.601 (0.511)
Population density	-0.016 (0.031)	0.001 (0.005)	-0.002 (0.009)	-0.032 (0.037)
Sheeps and goats density	-0.033 (0.034)	-0.006 (0.005)	0.005 (0.006)	-0.002 (0.011)
Constant	-17.452 (22.423)	-3.340 (3.721)	-8.707 (12.781)	2.696 (11.469)
Observations	123	250	195	195
R^2 McFadden	0.193	0.110	0.140	0.059
Likelihood-ratio test (p-valor)	9.27 (0.234)	30.78 (0.0)	11.01 (0.138)	4.65 (0.70)
AIC	54.68	296.29	83.88	90.239

Table 10. Logistic regression (odds-ratio) on any wildfire in municipality in the buffer between 2001 and 2015 by type of cause

Given the loss of observations due to variable *Vegetation* in Table 10, in Table 10same regressions are performed omitting the variable *Vegetation*. Broadly speaking, the results of the different explanatory variables are maintained while, at the level of the La Rioja variable, the non-significance in the specifications of wildfires with a lightning or unknown cause is maintained while for the causes of intentional or negligence fire, they are negative and significant. More specifically, in the case of the specification of intentionally caused fires, in *La Rioja* there is a 65% decrease in the probability of at least one fire due to intentional cause, keeping the other variables constant. On the other hand, there is a 92% lower probability of at least one fire in La Rioja due to negligence than in the buffer area of Castilla y León.

	Lightning	Intentional	Negligence	Unknown
	Coef. (Error. St.)	Coef. (Error. St.)	Coef. (Error. St.)	Coef. (Error. St.)
La Rioja	-0.176 (1.239)	-1.047*** (0.375)	-2.534** (1.220)	-0.867 (0.816)
Surface	0.014 (0.013)	0.004*** (0.006)	-0.004 (0.010)	-0.004 (0.012)
Altitude (log)	0.726 (1.987)	-1.915 (0.700)	-0.415 (1.421)	-0.484 (1.383)
Population (log)	-0.991 (0.792)	0.214 (0.191)	0.460 (0.361)	0.659 (0.519)
Population density	-0.006 (0.022)	-0.002 (0.005)	-0.001 (0.008)	-0.039 (0.044)
Sheeps and goats density	-0.019 (0.034)	-0.005 (0.005)	0.0022 (0.006)	-0.005 (0.012)
Constant	-8.352 (14.418)	11.072 (4.996)	-1.979 (9.891)	-2.186 (9.791)
Observations	250	250	250	250
R^2 McFadden	0.060	0.090	0.134	0.059
Likelihood-ratio test (p-valor)	3.38 (0.760)	25.24 (0.0)	11.22 (0.134)	4.97 (0.545)
AIC	67.23	268.81	86.76	93.02

Table 11. Logistic regression (odds-ratio) on any wildfire in municipality in the buffer between 2001 and 2015 by type of cause and without vegetation variables

2.2.6. Approach to the cost-benefit analysis of the measure

For a cost-benefit analysis, a determination of possible costs and benefits, as well as their monetary valuation, must be carried out. While in an economic-financial analysis we will only take into account cash flows, in a cost-benefit analysis we must also take into account social costs and benefits (Table 12).

To estimate the social value of the policy we must choose the time horizon and the social discount rate to update the different flows. As for the time horizon, we will choose the time period from 2001 to 2015. Since clearing was done prior to 2001, we can consider that in our time period there is a steady state between costs and benefits. That is, both at the beginning and at the end of our period, the costs and benefits are constant.

Costs and benefits valuation will be made through market prices. However, in many cases a direct assessment of these is not possible, so it will be necessary to look for the best criterion in the absence of it. For market prices, regulated or subsidized public prices cannot be used, as well as prices that include fiscal requirements, such as VAT or other indirect taxes. In the case of indirect taxes, they will not be included when they are a transfer but when it is a predisposition to pay.

Benefits	Costs
Reducing wildfires extinguishing costs	Cost of clearing
Reducing wildfires economic losses	
Reducing wildfires externalities	
Clearing positive externalities in other sectors	

Table 12. Clearing benefits and costs

To quantify the clearing cost in the buffer we know that 18,918 hectares have been extended during this period throughout La Rioja (Lasanta et al., 2022). From the IV Forest Inventory of La Rioja and, assuming that the proportion cleared is the same in the buffer as in La Rioja, we obtain those 12,789 hectares has been cleared in the buffer between 2001 and 2015. If we assume an average cost of € 434.27 per hectare in 2021 (data for internal use by the government of La Rioja), the expenses in clearing amount to € 5,553,879.

To quantify the reduction in wildfire extinguishing expenses and losses linked to wildfires, we need to know how many hectares would have been burned in the Rioja buffer area if the clearings had not been carried out between 2001 and 2015. If we choose the model with a lower Akaike of Table 9.

In this chapter it has been possible to evaluate and quantify the reduction of extinguishing expenses and economic losses of wildfires due to clearings. It would be necessary to estimate other benefits linked to clearing, such as the lower negative externalities derived from the reduction in the risk of wildfires (greenhouse gas emissions, biodiversity ...) as well as positive externalities that clearings may be causing, as is the case of the creation of jobs and diversification of the local economy. The economic valuation of these concepts would allow us to carry out a complete evaluation of the clearings.

2.3. Discussion

One of the most important results of this chapter is that clearings would be reducing between 67 and 77% the probability of at least one forest fire in a municipality of La Rioja between 2001 and 2015 compared to a municipality of Castilla y León. Lasanta et al. (2022) provide that in La Rioja an average of 1,060 ha per year were burned between 1968 and 1986, while from 1987 to 2020 it was 221.7 ha/year. This is a reduction of 79% between before and after the entry into force of the policy of stays in La Rioja. If we match this statistic with our time period of analysis, from 2001 to 2015, we find that the forest area burned in La Rioja has been 146.63 ha per year. This reduction would therefore be 86.2%.

A second result to highlight is the reduction in the number of fires linked to intentional causes, as well as negligence or accidents in the Rioja buffer area. With the available data, this difference cannot be directly attributed to the clearing policy in La Rioja, nor can it be ruled out that this is the main reason for this reduction. It should be remembered that the clearings aim to reduce biomass creams, which can be the origin of many fires caused by accident or negligence, or even intentional cause. Therefore, although this reduction in fires cannot be automatically attributed, there are sufficient reasons to think that this reduction is due to clearing.

A third result linked to wildfires are the avoided direct costs per hectare burned. In La Rioja, this figure is € 1,411.58 taking into account the expenses of extinction and losses linked to fires. Much of this differential is due to avoided losses (€1,036.56) rather than extinguishing costs (€375.02).

This magnitude is not all the costs avoided per hectare by the policy of clearing wildfires, since the economic valorization of the negative externalities linked to forest fires should be included, in order to be able to make an assessment of both.

Thus, it is a credible indicator that quantifies the avoided costs in wildfires thanks to clearing. The conditions closest to an almost experiment have been reproduced to give legitimacy to the indicator being impartial and unbiased. It is relevant because it can be used in cost-benefit analysis of clearings, and it is feasible because it has been obtained in time, adequate effort and availability of data.

A fourth and final result, linked to the fixation of population in the territory, is that no loss of population is detected in areas where clearing has been carried out. Although the evidence is not conclusive, it does seem to indicate that in areas where clearing has been carried out, the fall in population has been smaller or, even, there have been population gains.

On the other hand, clearings also generate positive effects not only in the reduction of forest fires, but also in the production of blue water. Fourth chapter is an evaluation of the clearings on the greater availability of water.

One of the characteristics of this evaluation is its replicability. On the one hand, since it is public data, this evaluation can be replicated both to confirm the results and to extend it. And, on the other hand, the clearing policy can be replicated elsewhere and its effects evaluated.

3. Evaluation of preventive measures for reducing the propagation of wildfire

For this chapter of the report, we evaluate land intervention measures in the area of the study that help to reduce the propagation of wildfire. Possible intervention measures include planting a natural barrier in form of cultivated vineyards, man-made fire breaks or interventions that aim to reduce the fuel load of the forest like grazing or clearing the understory. In this respect the analyzed land-intervention measures are more generic and comprehend several of the 15 land-intervention measures. For this part of the study the four dimensions of the socioeconomic evaluation give rise to the following four indexes

- Efficiency:

  Indexes: Optimal level of the extension of random and strategically implemented intervention measures.

- Effectivity:

  Indexes: The size of the forest area that is saved from being burnt as a result of intervention measures. The amount of CO_2 avoided as a result of intervention measures.

- Cost Benefit Analysis:

  Index: Cost Benefit calculations

- Replicability:

  Index: A computer program based on Monte Carlo simulations

For the calculations of these indexes, we define that the share of forest land that is saved from being burnt as a function of the EXTENSION RATE and EFFICIENCY RATE of the interventions. The dimension extension rate measures the share of the forest land that has been intervened and the dimension efficiency rate the probability that the intervened area act as a wildfire break. The dimension efficiency rate is relatively low if the understory is only taken out every 15 years instead of every 5 years and it is relatively high if vineyards act as a wildfire break. We calculate the share of the land saved from being burnt by a Monte Carlo Simulation explained below.

3.1. Monte Carlo Simulation

The results of the Monte Carlo simulation are dimensionless and as such they are applicable to any forest. To facilitate the interpretation of the results we use the program EXCEL as it runs under many operating systems. The Excel program with the file name

“ForestIntervent.xsxl” could be located at a public repository so that it can be widely used. For adjusting the EXCEL program to the users’ need the program allows to enter forest specific data. The input field for these data points are marked in yellow – see for example Figure 11. In contrast, numbers in red indicate output of the program.

TOOL FOR THE COST-BENEFIT ANALYSIS OF WILDFIRE PREVENTION

	VALUES
Size of the forest land (ha)	10000
Total area burnt per year (ha)	180
Burnt ha per fire	12
Numer of wildfires per year	15
Average monetary damage of a burnt ha (€)	5000
Efficiency rate - **pulldown menu**	60
Minimum costs per ha for the chosen intervention measure	50
Maximum costs per ha for the chosen intervention measure	80
Optimal extension o the intervention (% of forest)	3,2
Biomass (m^3/ha)	347
Density of the biomass (kg/m^3)	1200
Share of carbon of the biomass (%)	0,5
Carbon content of the biomass (kg/m^3)	600
Carbon fire emissions without intervention (t)	37.476
CO_2 fire emissions without intervention (t)	137.412
Saving rate of the carbon emissions by the optimal extension of the intervention (%)	56%
Carbon emissions avoided by the optimal extension of the intervention (t)	20.892
CO_2 emissions avoided by the optimal extension of the intervention (t)	76.605

Figure 11. Screenshot of the sheet “Cost Benefit Analysis” of the EXCEL program where user input fields are marked in yellow.

Exogenous data supplied by the user

Size of the forest land (ha): LSize

Total area burnt per year (ha): BurntHa

Number of wildfires per year: NumFire

Average monetary damage of a burnt ha: DamageHa

The efficiency rate (%) of a specific intervention measure from the set {0, 10, 20, …, 100}:

Efficiency

Minimum Intervention cost per ha/year realizing the chosen intervention: minC

Maximum Intervention cost per ha/year realizing the chosen intervention: maxC

Biomass (m^3/ha): Biomass

Density of the biomass (kg/ m^3): Density

Share of carbon of the biomass (%): ShareCarbon

The names in green indicate the names of the parameters that are used in this part of the report.

For this section we discuss the first three input variables and the remaining seven are discussed in Section 3.3. The input data LSize refers to the average total size of the forest over a given time span. Moreover, we consider that the forest is NOT divided by significant natural barriers that impede the wildfire to spread. If it is the case the user should consider each part of the forest individually and use the program with specific data for the different part of the forest. The input data BurntHa refers to the average number of ha burnt per year over the given time spam. The last input data refers to the average number of wildfires over the given time spam. Based on the data we can calculate the probability that a wildfire starts at any ha of the forest. For example, the user has entered the following data:

LSize = 10000ha, BurntHA = 180, NumFire = 15.

Thus, the average size of a wildfire = BurntHa/NumFire = 180/15 = 12 ha and the probability that a fire starts at any of the 10000 ha is NumFire/LSize = 15/10000 = 0.0015. In other words, at any ha a wildfire starts with probability 0.0015 and burns on average 12 ha (in the Excel program numbers marked in red indicate the results of calculations opposed to parameters or input data). In our conceptual framework we do not consider the direction wildfire takes as is advances. We also do not consider that a wildfire may start near the edge of the forest and as a result of the prevailing winds it progresses towards the edge of the forest. However, its propagation may be limited since the edge of the forest is formed by a natural barrier like a lake or bare agricultural land. Within this setup the forest land is thought of a borderless area where all edges are connected with each other. Obviously, it is a generalization, but we consider that the introduced error is negligible and affects the results of the simulation only insignificantly.

The data BurntHa and NumFire are specific for each forest not only because of the natural conditions (e.g., fuel load, intensity of heat waves, precipitations), human activities but also because of the capacity to extinguish the fire (accessibility of the land for firefighters, equipment of the firefighters).

For the Monte Carlo simulation we consider the efficiency rates (%) 0, 10, 20, …, 100 and the extension rate (%) 0, 1, 2, 3, …, 50. The simulation realized with the program Mathematica® allows to produce the following Table 13.

For example, the table indicates for an intervention measure with an extension rate of 3% and an efficiency rate of 10% that 13% of the burnt area can be saved by this intervention. For this purpose, we simulate the ignition of a wildfire and calculate the average susceptible number of burnt ha for every ha of the forest as a starting point of the wildfire. The ignition of the wildfire is modeled by the WildfireArray and the average susceptible number of burnt ha by the InterventionArray and the BurntHaArray. In the following two sections we discuss the underlying calculations realized by the Mathematica® program. The program code is available in Appendix 1.

EXTENSION	EFFICIENCY										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
1%	0	4	9	13	17	21	24	28	32	33	35
2%	0	9	18	25	31	35	42	47	51	54	57
3%	0	13	25	35	42	48	54	59	63	67	68
4%	0	17	30	42	50	57	62	67	70	73	76
5%	0	21	37	49	56	63	69	73	77	79	82
6%	0	25	42	55	61	69	73	77	80	81	84
7%	0	28	46	59	67	73	76	80	82	86	86
8%	0	31	50	63	70	76	80	83	84	87	88
9%	0	34	54	65	73	78	82	85	87	88	89
10%	0	36	58	69	76	80	84	86	88	90	91
11%	0	40	59	71	78	83	85	87	89	90	91
12%	0	42	63	73	80	84	87	89	90	91	92
13%	0	44	65	75	81	86	88	90	91	92	93
14%	0	46	67	77	83	86	88	91	92	93	94
15%	0	49	69	79	84	87	90	91	92	94	94
16%	0	50	71	79	85	88	91	91	93	93	94
17%	0	52	72	80	86	89	91	92	93	94	95
18%	0	54	73	82	87	89	91	93	94	94	95
19%	0	56	75	83	87	90	92	93	94	95	95
20%	0	57	76	84	88	90	92	93	94	95	95
21%	0	58	77	84	88	91	93	94	95	95	96
22%	0	60	78	85	89	91	93	94	95	96	96
23%	0	61	79	86	90	92	93	94	95	96	96
24%	0	63	80	86	90	92	94	95	95	96	96
25%	0	63	80	87	91	92	94	95	95	96	97
26%	0	65	81	88	91	93	94	95	95	96	97
27%	0	65	82	88	91	93	94	95	96	96	97
28%	0	67	83	89	92	93	95	95	96	97	97
29%	0	68	83	89	92	94	95	95	96	97	97
30%	0	69	84	89	92	94	95	96	96	97	97
31%	0	69	84	90	92	94	95	96	96	97	97
32%	0	71	85	90	93	94	95	96	97	97	97
33%	0	71	85	90	93	94	96	96	97	97	97
34%	0	72	86	91	93	95	95	96	97	97	98
35%	0	73	86	91	93	95	96	96	97	97	98
36%	0	73	87	91	94	95	96	97	97	97	98
37%	0	74	87	92	94	95	96	97	97	98	98
38%	0	75	87	92	94	95	96	97	97	98	98
39%	0	75	88	92	94	95	96	97	97	98	98
40%	0	76	88	92	94	95	96	97	97	98	98
41%	0	76	88	92	94	96	96	97	97	98	98
42%	0	77	89	93	95	96	96	97	97	98	98
43%	0	77	89	93	95	96	97	97	98	98	98
44%	0	78	89	93	95	96	97	97	98	98	98
45%	0	78	89	93	95	96	97	97	98	98	98
46%	0	79	90	93	95	96	97	97	98	98	98
47%	0	79	90	93	95	96	97	97	98	98	98
48%	0	80	90	94	95	96	97	97	98	98	98
49%	0	80	90	94	95	96	97	98	98	98	98
50%	0	81	91	94	96	97	97	98	98	98	99

Table 13. Average saving potential (percentage) of the number of burnt ha as a function of the extension and efficiency rates

3.2. WildfireArray

Based on the data input by the user the program determines the probability of wildfire ignition for a given ha. We assume that the probability for wildfire ignition is uniformly distributed over the forest land. The WildfireArray is of length 100 and each ha is assigned randomly with the calculated probability of wildfire ignition the number 1 and with the complement of the probability of wildfire ignition the number 0. The first 9 elements of the WildfireArray of length 100 may take the form

0	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**

For this array we find that the third ha caught fire and the others not. The program repeats this process 1000 times so that we have 1000 WildfireArrays of length 100.

3.2.1. InterventionArray/PossibleBurntHaArray

We consider the burnt area as an array with a length of 100, i.e., we can interpret our results as percentage. We denote this array InterventionArray. By convention, but without loss of generality, we assume that the wildfire starts, if it starts, always at the first element (ha) of the InterventionArray. According to the extension rate we randomly assign intervention measures with a given efficiency rate to the elements of the array. In this way we assume that the probability of the realization of interventions is uniformly distributed over the forest land. In other words, interventions are not strategically placed. Later, we extend the model and allow for strategic realization of interventions within the forest land.

For example, if the extension rate is 3% and the efficiency rate 100% each ha is assigned with probability 0.03 the intervention measure with an efficiency rate of 100% and with probability 0.97 the number 0 indicating that no intervention takes place. After this random assignment with probability 0.03 the first nine elements of the InterventionArray of length 100 may take the form

0	**Intervention**	**0**	**0**	**0**	**0**	**Intervention**	**0**	**0**

The susceptible "number of burnt ha" for the considered ha is 1 – taking into consideration that the wildfire always starts at the first element of the InterventionArray and the efficiency rate of the intervention is 100%. The term susceptible number of burnt ha indicates the extension of the forest fire if the first ha of the wildfire is set on fire. For the Monte Carlo Simulation we generate 1000 InterventionsArrays for the extension rate 3% and efficiency rate 100%. If the efficiency rate was 10%, we would calculate the susceptible number of burnt ha as the expected susceptible number of burnt ha. For the considered case the expected susceptible number of burnt ha of the InterventionsArray is given by the (cardinality of the first interval of zeros)$^{0.9*0}$ + (cardinality of the second interval of zeros)$^{0.9*1}$ + (cardinality of the third interval of zeros)$^{0.9*2}$ and so forth. Taking the mean of the susceptible number of burnt ha yields the average susceptible number of burnt ha over all 1000 InterventionArrays for the extension rate 3% and efficiency rate

10%. Accordingly, we calculate the mean of the susceptible number of burnt ha for each of the remaining combinations of the extension and efficiency rates. The mean of the susceptible number of burnt ha for each of the 1000 InterventionArrays yields the SusceptibleBurntHaArray of length 1000. For example, for the combination of the extension rate of 3% and efficiency rate of 100% the first 9 elements of the SusceptibleBurntHaArray may take the form

13.12	**31.23**	**9.22**	**41.87**	**58.30**	**43.82**	**27.32**	**12.98**	**23.82**

The SusceptibleBurntHaArray shows that the average susceptible number of burnt ha is 13.12 if the first ha catches fire and 31.23 if the second ha is the starting point of a wildfire. Yet, the elements of the SusceptibleBurntHaArray, e.g., 13.12, should not be interpreted as ha but rather as the percentage of the value BurntHa that has been specified by the user.

3.2.2. BurntHaArray

For actual calculation of the burnt ha we multiply each element of the WildFireArray with the corresponding element of the SusceptibleBurnHaArray. In other words, for every ha we determine whether the ha in position "x" of the Wildfire was a starting point of a wildfire or not. In case it was, the susceptible number of burnt ha becomes the number of burnt ha. If it was not the starting point of a wildfire the number of burnt ha is equal to 0. For the examples of the WildFireArray and the SusceptibleBurntHaArray presented above the BurntHaArray becomes

0	**0**	**9.22**	**0**	**0**	**0**	**0**	**0**	**0**

The value 9.22 indicates the percentage of the input date BurntHa specified by the user for the considered extension and efficiency rates. Accordingly, we multiply the WildFireArrays and SusceptibleBurntHaArrays for all combinations of the extension and efficiency rates. The results are summarized in Table 13 as a relative value in percentage. In the excel program – ForestIntervent.xslx – the values of Table 13 are translated in the absolute number of ha that are saved of the BurntHA specified by the user as a function of the extension and efficiency rates. Thus, if the user has specified that BurntHa is equal to 180 the reduction in the burnt area is 180 x 0.0922 = 16.60.

3.3. Cost-benefit analysis of the forest intervention

The Excel program requires the user to specify three different economic data in order to compare the costs and benefits of specific intervention measures chosen by the user of the program.

Exogenous data supplied by the user:

Average monetary damage of a burnt ha including the costs of fire extinction[1] and the deterioration of the ecosystem services of the forest: DamageHa

The efficiency rate of a specific intervention measure[2] from the set {0, 10, 20, …, 100}:

Efficiency

Minimum Intervention cost per ha/year realizing the chosen intervention: minC

Maximum Intervention cost per ha/year realizing the chosen intervention: maxC

Biomass (m^3/ha): Biomass

Density of the biomass (kg/ m^3): Density

Share of carbon of the biomass (%): ShareCarbon

The data about the intervention costs are inquired from the user since we consider that the costs of the intervention are minimal if the extension rate of the intervention is small. Forest managers can choose the sites where the costs are smallest (highly accessible ha, natural characteristics of the terrain are favorable (plain terrain, good soil). However, as the extension rate increases the sites are less accessible and the natural condition are less favorable so that the intervention costs increase. We hereby assume that preventive measures are realized first where the costs are lowest, and as preventive interventions are extended the costs increase.

Based on the user input data and the information provided by Table 13, Figure 12 illustrate the avoided average monetary damage (benefit) of the burnt area as a function of the extension rate of the intervention - green line. The orange line in Figure 13 presents the costs of the intervention as a function of the extension rate. Thus, the intersection of these two curves presents the optimal extension rate[3] given the data chosen by the user. The Excel program provides numerical value of the optimal extension rate. It is given by 3.2 % of the extension of the forest. The axis "Efficiency" can be extended up 50%. However, for the graphical presentation for the case at hand we only included the extension rate up to 4%.

[1] Information about average and median value of the damage of wildfire can be found at https://civio.es/espana-en-llamas/metodologia/.

[2] The program requires that the user has information about the efficiency rate, either through experimental data or through computational simulations.

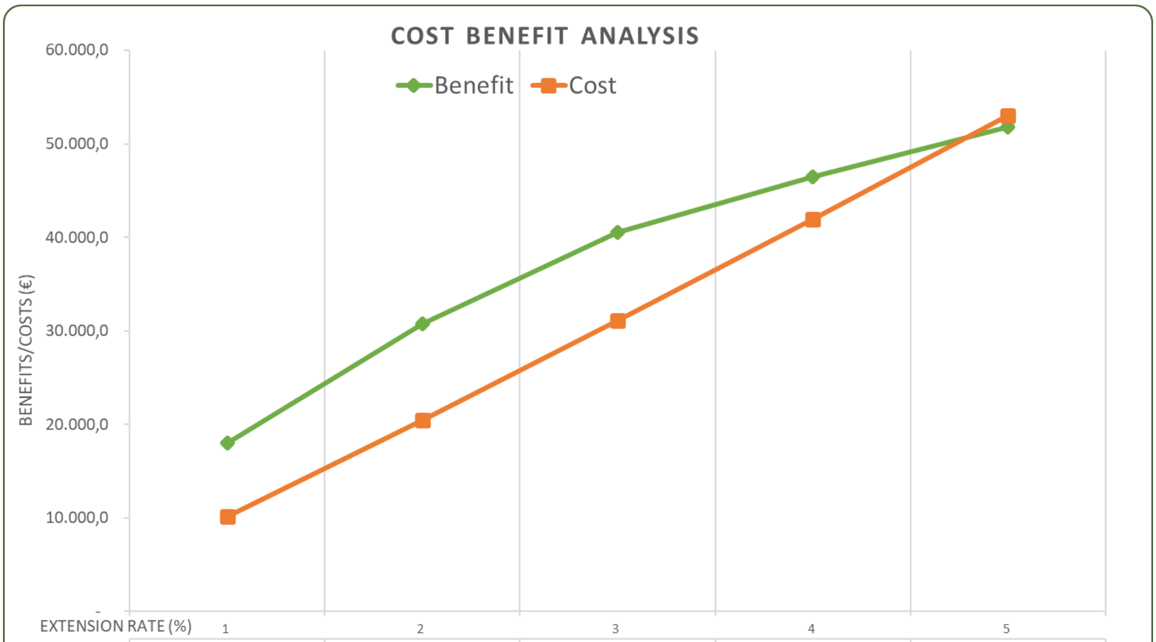
[3] This rate is optimal in the sense that a further extension of intervention measures leads to no additional net benefits. It does not maximize the net benefits by equating marginal benefits and marginal costs.

Figure 12. Avoided average monetary damage of the burnt area and the costs of the intervention measure as a function of the extension rate with monetary damage per ha = 5000, minimum costs = 50, maximum costs = 80, efficiency rate = 0.6, number of wildfires = 15

The Excel program also determines the avoided carbon (CO_2) emissions as a result of the optimal extension of the intervention measure – see also Figure 11. For this purpose, the user of the program has to specify the following information: Biomass (m^3/ha) (Biomass), Density of the biomass (kg/m^3) (Density), and the share of above- and below-ground carbon of the biomass (%) (ShareCarbon). The multiplication of the last two variables yields the carbon content of the biomass (kg/m^3). The multiplication of this value with Biomass times BurntHa yields the total emission of carbon per year from forest wildfire. The program calculates these emissions in terms of tons of carbon and in terms of tons of CO_2. As explained above the optimal extension of the intervention allows to reduce area BurntHa by the percentage specified in Table 13. Thus, the optimal extension of the intervention measure allows also reducing the total emission of carbon per year from forest wildfire by the percentage specified in Table 13. The program indicates the avoided emissions in terms of tons of carbon and in terms of tons of CO_2.

3.3.1. Sensitivity analysis

In case the user wants to explore the optimal extension rate for intervention measures with a different efficiency rates the user can change the value of the efficiency in the Excel program. Likewise, the user can modify the average number of fires, the average size of the burnt area, the monetary damages per ha or the minimum or maximum costs of the intervention measure. The modified data is reflected in the newly produced Figure of the Excel program. As an example, we present the results of a change in the user input specified in 3. The new user input data is specified in the legend of Figure 13 and a comparison with the legend of Figure 12 shows that the number of wildfires was reduced from 15 to 12. As a result, the optimal extension rate increases from 3.2 to 4.8. At first sight this result is counterintuitive, but one has to remember by reducing the number of wildfires by 20% the size of each fire increases by 25% if the total number of burnt ha is not modified.[4] In this situation the reduction in wildfires leads to more extended fires that require higher extension rates. However, if the number of wildfires is reduced from 15 to 12 and the total burnt area is reduced by 20% from 180 to 144 the optimal extension rate is again 3.2. This example explains that changing the number of wildfires only changes the probability of the ignition of a wildfire but without changes the total burnt area the probability of the wildfire propagation is increased. Thus, changes in these two parameters have to be considered simultaneously.



	1	2	3	4	5
Benefit	18.000,0	30.750,0	40.500,0	46.500,0	51.750,0
Cost	10.120	20.480	31.080	41.920	53.000

Figure 13. Average monetary damage of the burnt area and the costs of the intervention measure as a function of the extension rate with monetary damage per ha = 5000, minimum costs = 50, maximum costs = 80, efficiency rate = 0.6, number of wildfires = 12.

The change in the user specified input data can be realized within the Excel program and does not require to run the Mathematica® program again because the output of this program is dimensionless and in relative terms. Moreover, changes in the wildfire probability leads to proportional changes of the relative number of the BurntHaArray.

[4] This variation is the result of the calculation of the average size of a wildfire:= BurntHa/NumFire = 180/12 = 15 ha.

Thus, the output of the Excel program can be updated directly from the existing output of the Mathematica® program.

The user may also change the efficiency rate of the intervention measure. For example, from 60 to 100%. Looking at the numbers of Table 13 shows that an extension rate of 1% allows to save 35% of the total burnt area. In our view this number has to be interpreted with care since extension and efficiency rates are in reality not completely independent. The so far employed approach assumes that the implementation measures were randomly placed over a hypothetical stripe of land (one dimensional) but not over two-dimensional space. The wildfire may hit the fire barrier but if the extension rate is low the wildfire may find a way round the barrier. Thus, with a low extension and a high efficiency rate it is likely that the wildfire cannot be blocked completely. Therefore, it is likely that the extreme combinations of the extension and efficiency rates overestimate the saving effects of the interventions measure. To address this problem, we analyze in the next section the strategic implementation of the intervention measures over space to reduce the spread of wildfires.

3.3.2. Strategic implementation of the intervention measures

For the analysis of strategic placement of intervention measures we consider the case of barriers that have an efficiency rate of 100%, i.e., they completely impede the propagation of wildfire. These measures include stripes of land that for example are cultivated with vineyards or have no fuel load at all. The objective of this part of the study is to calculate the number of ha that are saved from burning as a function of the number of barriers implemented. The determination of the optimal number of barriers to save a given percentage of the forest from being burnt depends on three parameters: the expected direction of the wind, the form of the borderline and size of the forest, and the difference of the angle between the expected direction of the wind and the direction of the longitudinal axis of the forest. For simplicity we assume that the form of the borderline of the forest can be approximated (a) by a rectangle[5] and (b) assuming that the angle of the expected direction of the wind and the angle of the shorter side of the rectangle is either 0º or 90º. For the calculation of the rectangle the user needs to specify the length of the greatest distance between two points located on the border of BurntHa. This parameter specified by the user is denoted by FireLength (m). The FireWidth (m) is obtained by the division of BurntHa/FireLength multiplied by 10000 to take account of the fact that BurntHa is expressed in ha and FireLength in meters. Apart from the approximation of the form of the borderline of the forest we also approximate the location of the rectangle with respected to the expected direction of the wind. For this purpose we define the parameter Angle that measures the angle between the longitudinal axis of the rectangle and the expected direction of the wind as shown in Figure 14.

[5] The forest is not modelled as a bounding rectangle but as a rectangle with an equivalent size of the real forest.

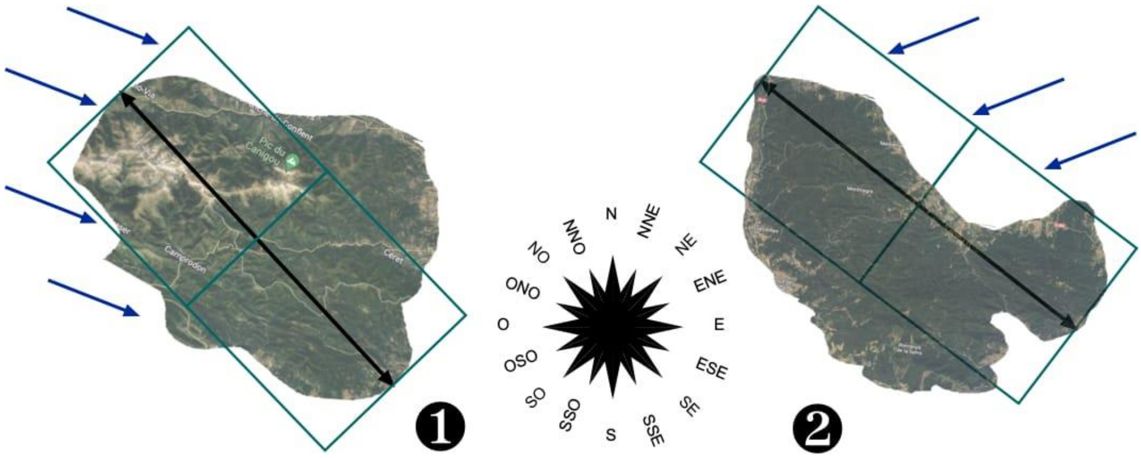


Figure 14. Illustration of the angle between the longitudinal axis of the rectangle and the expected direction of the wind

We distinghuish two cases. Case 1 is given when the value of Angle is either between 0º- 45º or between 315º - 360º. For Case 1 we assume that the width, or shorter side, of the rectangle is perpendicular to the expected value of the direction of the wind. Case 2 is given when the value of Angle is between is 45º - 90º or 270º - 315º and thus, the retangular is located such that the longer side of the rectangle is perpendicular to the expected value of the direction of the wind.

With respect to the hazard of the propagation of the fire the expected direction of wind of 0º and 180º are equivalent. Due due symmetry conditions of the circle taking the **absolute** values of the previous degree intervals minus 180º determines the location of the rectangle with respect to the expected direction of the wind. For example, 0º- 45º yields the interval 180º - 225º and 315º-360º yields the interval 135º - 180º. For both intervals the shorter side of the rectangle is located perpendicular to the expected value of the direction of the wind. For the example of shown in Figure 15 the relocation of rectangular forest yields

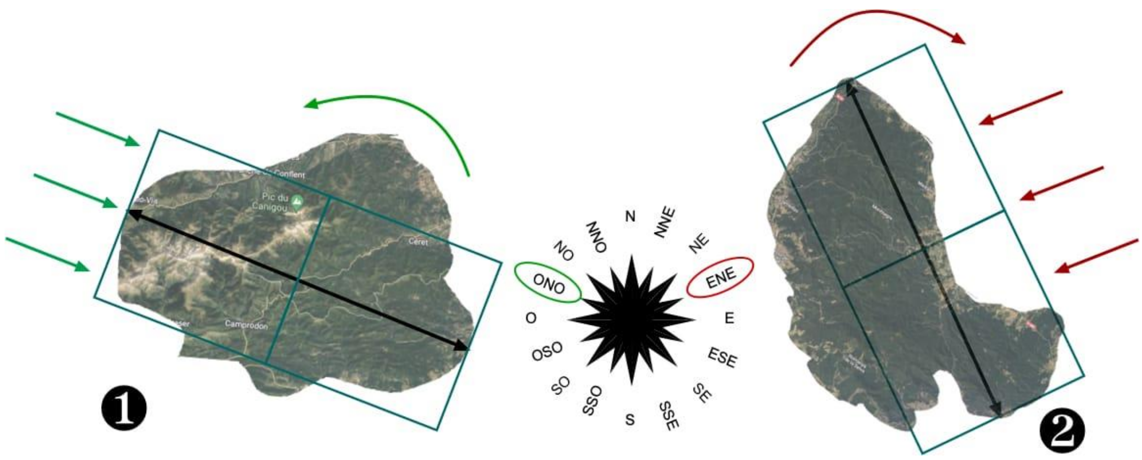


Figure 15. Relocation of the rectangular forest as a result of the value of Angle.

The relocation of the equivalent box is based on rotation. The box is rotated such that the expeced direction of the wind is either in line with the longitudinal or lateral axis of the box depending which of the two options requires a smaller angle of rotation.

For calculations realized by the program the user has to specify the direction of longitudinal axis of the forest and the expected value of direction of the wind based on the data of Table 14. These two parameters supplied by the user are denoted by LongAxis and DirectionWind respectively and chosen by the user from a drop-down menu on the sheet “Strategic Intervention” of th Excel program.

Direction	Angle (º) with respect to
E	0º
ENE	22.5º
NE	45º
NNE	67.5º
N	90º
NNW	112.5º
NW	135º
WNW	157.5º
W	180º
WSW	202.5º
SW	225º
SSW	247.5º
S	270º
SSE	292.5º
SE	315º
ESE	337.5º

Table 14. Angels of Direction, N = North, E = East, S = South, W = West

The length of the sides of the retangle is calculated from the variable ForestSize supplied by the user. If the borderline of the forest were quadratic with lengh “x” we determine a retangle with the same ForestSize, where the longer side is given by 2x and the shorter side by x/2. Thus the area of this retangle is given by 2x times x/2 = x^2. Thus, in general terms the longer side of the rectangle is equal to $2\sqrt{\text{ForestSize}}$ and the shorter side by $0.5\sqrt{\text{ForestSize}}$. Independent of the location of the rectangular Forest we denote the side of the rectangle that is perpendicular to the expected direction of the wind by ForestLength and the other side ForestWidth.

The previous analysis can be summarized in Table 15.

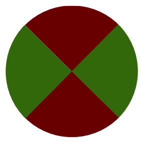
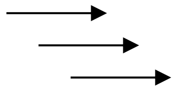
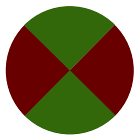
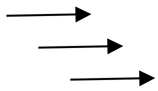
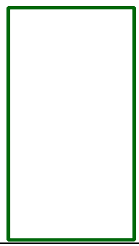
Angle between LongAxis and DirectionWind		Expected direction of the wind	Location of the rectangular forest: vertical ForestWidth times horizontal ForestLength
Case 1: Admissible angles of the direction of the wind, 315º - 45º and 135º - 225º (green area of the circleº			
Case 2: Admissible angles of the direction of the wind, 45º- 135º and 225º - 315º (green area of the circle)			

Table 15. Angels between LongAxis and DirectionWind and the location of the rectangular forest.

For the determination of the optimal number of barriers we first establish the location of the forest in form of a rectangle with respect to expected direction of the wind. For Case 1 the shorter side of the rectangle is perpendicular to the expected value of the direction of the wind and therefore, the number of barriers is higher, but the length of each barrier is less compared to the Case2. Each barrier has the width BarrierWidth specified by the user of the program. The implementation of barriers is guided by two principles:

1. The distance between two barriers is equal to FireLength – Barrier Width.
2. The number of barriers is determined by the integer number of ForestLength/FiresLength. The modulus of this division divided by two determines the distance between the borderline of the forest and the first/last barrier. Alternatively, the number of barriers can be increased by one if the modulus of the division is close to one.

For illustrating these two principles we refer to Figure 16 where each cell is of Length 1. We assume that FireLength is eight.

Barrier	**Cell 1 (1)**	**Cell 2 (2)**	**Cell 3 (3)**	**Cell 4 (4)**	**Cell 5 (5)**	**Cell 6 (6)**	**Cell 7 (7)**	**Barrier**	

Figure 16. Optimal distance between two barriers with an efficiency rate of 1.

If the distance between barriers were less than 7 the maximum area of forest saved from being burnt per barrier would decrease. If a fire that propagated to the right and started at cell 7 of Figure 176 (the first number in the cell) the barrier would avoid that the contingent 7 cells would get destroyed by the fire. Thus, the area saved from being burnt is 7 (the number in brackets. The same line of argumentation can be applied if the fire starts in any of the cells 6 to 1. Hence, the total area of forest saved from being burnt by the barrier is 7+6+5+…+1 = 28. This leads to the formula 0.5*NetFireLength*(NetFireLength+ 1), where NetFireLength is defined by FireLength – BarrierWidth. In the case of Figure 176 we have 3.5*8 = 28. In case the distance between barriers is less than NetFireLength, the total area of forest saved from being burnt by the barrier decrease. For example, if the distance between barriers were 6 the total area of forest save would 3*7 = 21. Likewise, if the distance between barriers were greater than NetFireLength, a wildfire originating in the most distant cell from the next barrier would not be stopped by the barrier. Hence, the contribution of the next barrier for saving forest land from being burnt would be zero for wildfires starting at cells more distant than FireLength.

Another way to illustrate the optimal distance between barriers is shown in **Error! Reference source not found.**7. The barriers are presented by the yellow lines and the FireLength by the length of the red rectangles. The green areas illustrate the areas of the land that are saved from being burnt. If the distance between the barriers is larger than the FireLength the barriers are less effective since they do not help to reduce area of land that is burnt for fires that at the beginning of the distance between the two barriers.

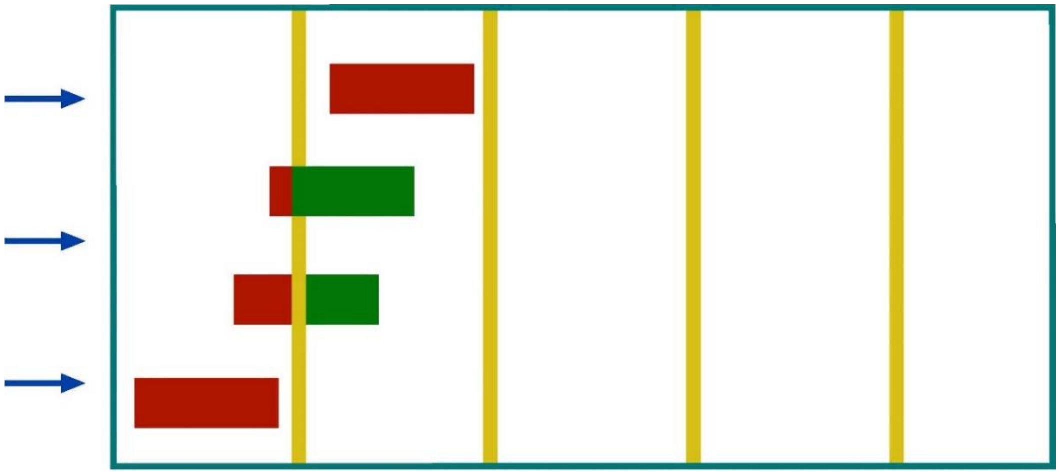


Figure 17. Distance between barriers and reduction in the area of land that is burnt

For the illustration of the management of the program we present a screenshot of the program in Figure 18. It corresponds to the Excel sheet "Strategic Intervention". As mentioned above the input that has to be supplied by the user is highlighted in yellow. Values highlighted in blue indicate that they were already supplied in the Sheet "Cost Benefit Analysis" and as such they should be modified only in the Sheet "Cost Benefit Analysis". Values in red indicate that they are the results of calculations. The final results of the evaluation of strategic intervention measures are highlighted in light green.Figure 18 shows for the considered forest that the strategic implementation of one barrier with a width of 50 m corresponds to an extension rate of 0.7% and allows to save 7% of the BurntHa to be saved from being burnt. Two barriers allow to reduce the burnt ha by 14% and 3 barriers by 21%. If the objective is to save 50% (planned saving rate) of the burnt area, one needs to set up 6.7 barriers. Since the BarrierWidth = FireLength – NetFireLength, part of the burnt area is already lost by setting up the barrier. For this reason, given the example in Figure 18 the net saving rate of the area BurntHa is 49%. This percentage goes down as the BarrierWidth increases. With planned saving rate of 50% and 75% the number of ha saved are 88 and 132 respectively. For the planned saving rate of 50% and 75%, the intervened areas are 4.8% and 9.5% of ForestSize respectively. The newly resulting forest area net of the barriers are 9524 ha for the planned saving rate of 50% and 9048 ha for the planned saving rate of 75%.

direction	Angle	Orientation of the forest (LongAxis) - pulldown menu	Expected wind direction (DirectionWind) - pulldown menu	ForestSize	BurntHa	FireLength	BarrierWidth	NetFireLength		Number of barriers	Extension rate	Forest area saved from being burnt
E	0	E	S	10000	180	2100	50	2050		1	0.7%	7%
ENE	22.5	1	13	Ha	Ha	meters	meters			2	1.4%	14%
NE	45	0	270					0.7%	Intervention area for a single barrier	3	2.1%	22%
NNE	67.5	-180	90	270				4.8%	Intervention area for 50% objective	4	2.8%	29%
N	90							9.5%	Intervention area for 75% objective	5	3.5%	36%
NNW	112.5	type	ForestWidth (m)	ForestLength (	FireWidth (m)			9524	New forest area in ha at a 49% net saving rate	6	4.2%	43%
NW	135	bad	7071	14142	857			9048	New forest area in ha at a 73% net saving rate	7	4.9%	50%
WNW	157.5									8	5.7%	53%
W	180	Planned saving rate	50%	75%						9	6.4%	57%
WSW	202.5	Net saving rate	49%	73%				88	Saved area in ha (planned saving rate 50%)	10	7.1%	61%
SW	225	Optimal number of barriers	6.7	13.5				132	Saved area in ha (planned saving rate 75%)	11	7.8%	64%
SSW	247.5	Distance between two barriers (m)	2075	1038						12	8.5%	68%
S	270									13	9.2%	72%
SSE	292.5									14	9.9%	73%
SE	315									15	10.6%	73%
ESE	337.5											

Figure 18. Screenshot of the sheet "Strategic Intervention" of the Excel program where user input field are market in yellow. Blue fields indicate data that user supplied in the sheet "Cost Benefit Analysis"

3.4. Results

The socioeconomic evaluation of land-intervention measures that aim to reduce wildfire propagation recognizes that a general evaluation is not very meaningful. The large variety of conditions (geographic conditions, type of forest, climatic conditions, human activities etc.) makes it impossible to obtain general results that are representative for the analyzed land-intervention measures. For this reason, we developed an Excel program based on the results of a Monte Carlo simulation. The program determines for a given efficiency rate the optimal level of the extension of randomly placed land intervention. The results show that even with a low extension rate the burnt area can be reduced substantially. For instance, with an extension rate of 2% and an efficiency rate of 50%, the burnt area can be reduced by 35% (index effectivity). The program also calculates the corresponding reduction of CO_2 emissions (index effectivity). Based on the reduction of the burnt area the program calculates the benefits and combines them with the costs of randomly placed land-intervention measures (index cost benefit calculations). Taking costs and benefits together allows determining the extension of these land-intervention measures from where on the costs of any further extension of the intervention measure exceeds its benefits. This critical value is denoted the optimal extension of the land-intervention measure (index efficiency). The analysis is extended by considering strategically placed land-interventions measures. The program determines the optimal number of fire barriers for a planned reduction of the burnt area by 50%. Moreover, the results show that the length of the longitudinal axis of the extension of the fire determines the distance between two fire barriers (index efficiency). The program also offers the optimal number of fire barriers for a planned reduction in the burnt area by 50% (index efficiency). Finally, the index replicability corresponds to the Excel program itself and the publication of the Mathematica® code for the replication of the Monte Carlo simulation in Appendix 1.

4. Evaluation of adaptation measures – increase in water resources

The progressive rural abandonment of the last decades has caused the expansion of unmanaged forest areas, which are responsible for the observed increase in interception and evapotranspiration. This growth of vegetation has affected the hydrological dynamics and led to a reduction in available water resources at the basin level (less blue water). In this sense, adaptation measures consisting of an improved and more extensive forest management (such as the reduction of stems per hectare and/or shrub clearing) can cause an increase in infiltration and runoff. These actions may result in increased availability of blue water, that can revert to greater economic activity and an improvement in aquatic ecosystems.

At the stand or plot level, some authors have found that brush clearing and/or thinning seem to increase water flows (Nadal-Romero et al., 2013, 2018). In locations where specific and detailed hydrological monitoring has been carried out, the data obtained show the potential of the management measures. For example, within the framework of the LIFE Climark project, coordinated by the Forest Ownership Centre of the Catalan Government (Catalan Water Agency, 2022), a significant increase in the flows of the Marimon Spring was observed after a thinning carried out in 2019-20 on the Mas Marimon forest farm, in the municipality of La Llacuna (l'Anoia, Catalonia).

Field studies with rainfall simulations at the stand or plot level in the framework of the present LIFE MIDMACC project also suggest that management can lead to an increase in water resources. However, although the results are in line with the expectations, there is a large variability at the plot scale, and numerous experiments with long series are needed in order to observe statistically significant patterns.

However, these studies are essential as they enable better calibration of current hydro-ecological models, such as MEDFATE (De Cáceres et al., 2015) or RHESSys (Tague and Band, 2004). Studies using these models unquestionably show that adaptation measures can lead to a significant increase in the provision of blue water. Simulations carried out within the framework of the LIFE CLIMARK project applying different forest management treatments have obtained an increase in water resources between 26 and 367 mm per year (de Cáceres et al., 2022). In a study conducted in the Arnás catchment in the Central Pyrenees, Khorchani et al. (2020) modelled the clearing and cleaning of bushy areas and abandoned pastures. The treated area presents 15.75% of the catchment area and it is similar to the one treated in La Rioja (see chapter 2 of this report). The authors found that these measures reduce evapotranspiration and can improve the annual streamflow between 7.1% and 24.2% depending on the intensity of the clearing. In a parallel study of the Estarrún watershed in the Central Pyrenees, Khorchani et al. (2021) found that clearing 7.5% of the region would increase water flows by 6%, compared to the non-management scenario.

In Action C4 of the LIFE MIDMACC, which provides the scaling up to regional level of the climate change adaptation measures proposed in the project, an increase in water flows is also obtained as a result of land management in the mid-mountain area. This section presents the economic scaling of the three interventions analysed in Action C4. To do this, the estimated increases in water resources from the management interventions in several representative sites in the mid-mountain area are used, and the impact that these increases may have on the economy is inferred using the Input-Output (IO) methodology described in the following section.

4.1. Methodology and data

4.1.1. Socio-economic model

To examine the economic impacts of variations in water resources, resulting from climate change adaptation measures in mid-mountain areas, we use the Input-Output (IO) methodology developed by Leontief (1941). This is a standard methodology that has been widely applied in this field (Freire-González et al., 2018; Garcia-Hernandez and Brouwer, 2020; Martin-Ortega et al., 2012). In particular, we employ a variation of the IO model, corresponding to the supply-side approach (Ghosh, 1958). Following Proops (1988), the basic IO model is extended environmentally to the use of water resources by defining a vector of water use per unit (€) of output, that allows calculating the amount of water that is necessary to satisfy the final demands of the economy. In this way we obtain the total use of water resources in the economy, that is, the water directly and indirectly used to satisfy the final demands of a country or region. The model allows linking the economic activity with the impacts on water resources in a comprehensive way, that is, it considers the interconnections between all economic sectors. Once the base model representing the real situation in terms of water pressure has been calculated, it is possible to analyse the effect of an increase in the availability of water resources on the economy, in terms of the change in value added (VA).

Additionally, we must take into account that in a context of globalized economies, inputs, natural resources, and final products are increasingly interconnected through international trade and global supply chains. This entails the need to incorporate the interdependencies between the different regions and industries in the economic model. For this reason, we employ a multiregional IO model. The model is presented in Annex 2.

The socio-economic data for the analysis are obtained from version 3.7 of EXIOBASE (Stadler et al., 2019). The database provides information on economic linkages between 163 sectors in 44 countries (including Spain) and 5 aggregated regions — combined with multiple social and environmental satellite accounts. We consider EXIOBASE to be an optimal multi-regional IO database to perform the analysis because it follows the guidelines of the United Nations System of Environmental and Economic Accounting. It provides a high level of harmonised and comparable sectoral detail across countries for those economic activities that exert significant pressure on natural resources, which would allow replicating the analysis in other regions. In addition, it has a detailed breakdown for the agricultural sectors. This is particularly relevant when it comes to the valuation of water resources, as agriculture is the sector with the largest water use worldwide (more than 70% in Catalonia). Finally, it offers consistent, long and updated series. Specifically, we use information from the last five years 2014-2019[6] and calculate the average effects; in this way the results are not conditioned by the current economic situation.

The increase in the availability of blue water from the adaptation measures is applied proportionally to the water use of the different agricultural sectors. Since agriculture is the largest user of water resources, it is also the first to benefit from an increase in these resources, provided that the environmental requirements of the maintenance or ecological flows of the rivers are met. Furthermore, climate change will foreseeably cause an increase in the demand for agricultural water due to higher temperatures and

[6] We decided not to use the years 2020 and 2021 because they cannot be considered representative due to the great economic impacts of the COVID-19 pandemic.

the greater water needs of crops. Thus, an increase in the availability of blue water can help to alleviate scarcity and increase production. A relevant factor for the analysis is establishing the proportion of the increase in available water resources that that will be used for economic purposes, that is, that will serve to increase production. The calculations are based on the fact that the average water stress level in Spain in the last decade has remained above 40%,[7] specifically, it stands at 40.17% in 2019, which signifies a withdrawal of more than 40% of the available freshwater resources. In addition, agriculture accounts for approximately 80% of consumptive water use in Spain. Therefore, we assume that 32% (0.32=0.8x0.4) of the increase in water resources obtained by the measures will be used to increase agricultural economic activity. The remaining percentage will stay in the natural environment.

Once the additional available water volumes have been determined, it is necessary to estimate how the higher availability translates into aggregate production increments in each of the economic sectors. In order to obtain more precise estimates of these direct effects, we use the elasticities calculated by Roson (2019), which quantify the percentage change in sectoral production due to a relative change in available water. The increase in production in the primary sector will require an increase in inputs in sectors, which are indispensable for agricultural production. These in turn will require inputs from other sectors, generating a cascading effect. Once the direct increases in production have been calculated, we can estimate the indirect impact on the different sectors using the Ghosh approach, and the total final impact on the economy can be determined. It should be noted that the impact on the VA calculated in this way is more conservative than if the increase in water resources were applied to all economic sectors (agriculture, industry, and services) in proportion to their water use. In this report the most prudent approach has been considered. However, in years of extreme drought, the benefits obtained would increase if additional hydrological resources resulting from management measures can help alleviate water scarcity both in the agricultural and livestock sectors as well as in industrial sectors.

4.1.2. Hydrological data

In order to model the initial production increases, it is required to first estimate the increase in water availability as a result of the different adaptation measures. These actions have been modelled in Aísa (Aragon), the Leza valley (La Rioja) and the l'Anyet valley (Catalonia). Aísa covers an area of 77.24 km^2, and the modelled action consisted of clearing 6% of shrubland, with a consequent increase in the pasture area. In addition, a 50% thinning of the canopy cover is carried out in coniferous forests, which represent 27.12% of the territory. The second site, the Leza valley, occupies an area of 285.13 km^2. Here, the plausible shrubland area that is cleaned, in line with the criteria of the regional government, corresponds to 20% of the shrub-covered surface (9.7% of the total). In the l'Anyet basin (143.26 km^2) the clearing of abandoned crop fields is modelled. Moreover, approximately 50% of the initial *Quercus* forest area is cleared, i.e., the forest area decreases from 18.62% to 9.81% of the territory. Deliverable D17 of LIFE MIDMACC provides additional information on the places and measures analysed.

The impact of forest management on water supply is obtained by calculating the increase in water exported in the managed scenario compared to the scenario without management. The increase in blue water availability for the different locations and

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[7] World Bank Data, available at https://data.worldbank.org/indicator/ER.H2O.FWST.ZS?locations=ES

scenarios considered is shown in Table 16. It shows, in general, an improvement in the water balance resulting from management, compared to the no-management scenario. If the effects of climate change are not taken into account, management in the Leza valley leads to an increase in average streamflow of 0.1266 m^3/s (3.96 hm^3 per year), while in the l'Anyet valley the increase amounts to 0.0456 m^3/s (1.44 hm^3 per year). In contrast, management in Aísa would not be advisable from the specific point of view of water resources provision, since its availability decreases. In the modelling under climate change, the effects are positive for all considered scenarios, as it is shown in Table 16. In parallel to the scenarios that do not consider the effects of climate change, Table 16 illustrates that the greatest impact occurs in the Leza and l'Anyet valleys, while the changes for the Aragon region are much more moderate.

Average increase in streamflow (m^3/s)	Aísa (Aragon)	Leza (La Rioja)	L'Anyet (Catalonia)
No climate change	-0.00048	0.12666	0.04568
Ssp2.6	0.00084	0.12834	0.04282
Ssp4.5	0.00066	0.11267	0.04223
Ssp7.0	0.00231	0.11514	0.04164
Ssp8.5	0.00314	0.11585	0.03791

Table 16. Increase in blue water availability as a result of the actions.

In addition, it is necessary to consider the impact of interventions over time. The methodology proposed by the LIFE Climark assumes that the effect of the adaptation measures on the volume of additional water will extend beyond the period of action; in particular, it states that the impact is not constant but rather it decreases over time as the vegetation regrows. Khorchani et al. (2021) also point out that the increase in water flows after clearing cannot be considered stable over time. In a study in the Estarrún watershed in the Central Spanish Pyrenees, they found that the maximum streamflow change is reached in the second year after the interventions, and this improvement is diluted in the following years, reverting to the original situation in a period of five years. Thus, following Khorchani et al. (2021), a 5-year improvement period is assumed in this analysis. Specifically, the annual increase over the average increase is assumed to be 1.25, 1.75, 0.75, 0.6, and 0.6 in years 1 to 5, respectively.

4.2. Results

4.2.1. General results

The estimation of the impacts derived from the increase in water resources by 1 hm^3 on the economy is presented below. Subsequently, the specific calculations are made for the actions of adaptation to climate change in the mid-mountain areas established in the LIFE MIDMACC project. Table 17 shows the total, direct and indirect impact of a 1 hm^3 increase in water resources destined for production measured in terms of VA, disaggregated by economic sectors. The total impact is approximately 3.5 million euros, of which 275,424€ correspond to the direct impact on the agricultural sector, and 3,204,230€ to the indirect impact on all economic sectors thanks to the carryover effect of increased agricultural production.

Economic sectors	Total impact in € (%)		Direct impact in € (%)		Indirect impact in € (%)	
Cultivation of paddy rice	4,349	(0.12)	4,347	(1.58)	2	(0.00)
Cultivation of wheat	14,073	(0.40)	13,685	(4.97)	388	(0.01)
Cultivation of cereal grains nec	32,246	(0.93)	31,939	(11.60)	308	(0.01)
Cultivation of vegetables, fruit, nuts	150,000	(4.31)	144,723	(52.55)	5,277	(0.16)
Cultivation of oil seeds	33,805	(0.97)	33,729	(12.25)	75	(0.00)
Cultivation of sugar cane, sugar beet	1,385	(0.04)	1,385	(0.50)	0	(0.00)
Cultivation of plant-based fibers and other crops	18,251	(0.52)	18,239	(6.62)	12	(0.00)
Farming	38,728	(1.11)	27,377	(9.94)	11,351	(0.35)
Wool, silkworm cocoons and other animal products	1	(0.00)	-	-	1	(0.00)
Raw milk	1,210	(0.03)	-	-	1,210	(0.04)
Forestry, logging and related activities	45	(0.00)	-	-	45	(0.00)
Fishing	144	(0.00)	-	-	144	(0.00)
Mining and quarrying	204	(0.01)	-	-	204	(0.01)
Food and beverage processing/manufacturing	380,693	(10.94)	-	-	380,693	(11.88)
Other products manufacturing	43,044	(1.24)	-	-	43,044	(1.34)
Machinery, transport equipment and other manufacturing	41,314	(1.19)	-	-	41,314	(1.29)
Electricity, gas and water supply	14,322	(0.41)	-	-	14,322	(0.45)
Construction	93,130	(2.68)	-	-	93,130	(2.91)
Trade, hotels and restaurants	2,024,047	(58.17)	-	-	2,024,047	(63.17)
Transport, storage and communication	64,778	(1.86)	-	-	64,778	(2.02)
Financial intermediation y and related activities	244,879	(7.04)	-	-	244,879	(7.64)
Public administration, education, health care and extraterritorial organisations	228,740	(6.57)	-	-	228,740	(7.14)
Other community, social and personal service and household activities	50,266	(1.44)	-	-	50,266	(1.57)
Total	**3,479,653**		**275,424**		**3,204,230**	

Table 17. Impact of a 1hm^3 increase on water resources on VA

Table 17 also shows that the most important direct impact occurs in the cultivation of vegetables, fruits and nuts (52.55% of the total), in oilseeds (12.25%), and in the production of cereals (11.6%). On the other hand, several non-agricultural sectors also increase production significantly. The greatest effect is observed in wholesale and retail activities, hotels and restaurants, which accumulates 63.17% of the indirect effect and 58.17% of the total increase in VA. The effect on the processing and manufacturing of food and beverages is also important (10.94% of the total effect and 11.88% of the indirect effect).

4.2.2. Results for the study areas

The economic impacts for the areas of Aísa, Leza and l'Anyet are shown in Figure 20, Figure 21 and Figure 22, respectively, as well as in Table 18. The graphs illustrate the evolution of the change in VA or annual GDP over time, as a result of the modelled interventions, while Table 18 shows the Net Present Value of the increase in VA over the considered timeframe, discounted at an interest rate of 2%.

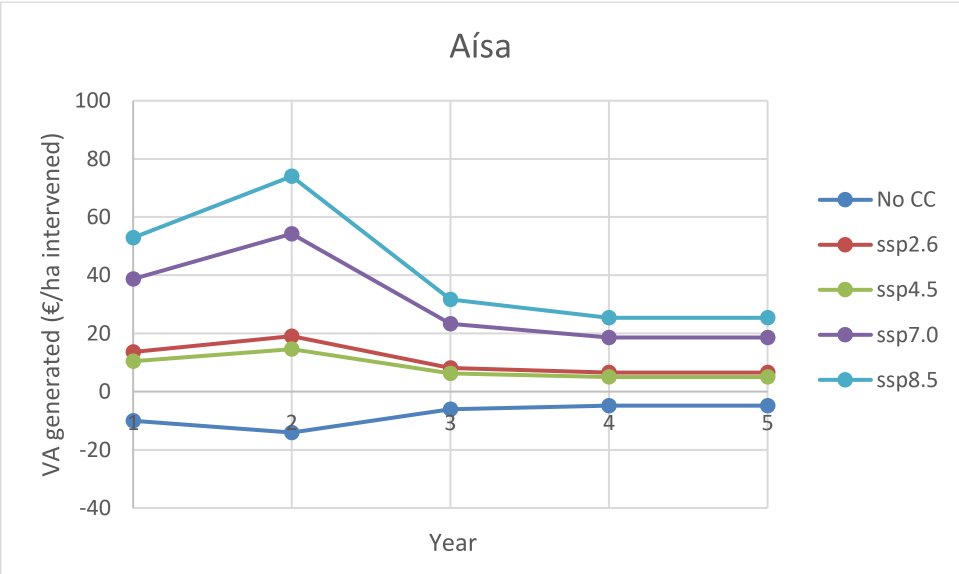

Figure 19. VA generated by the increase of water resources in Aísa

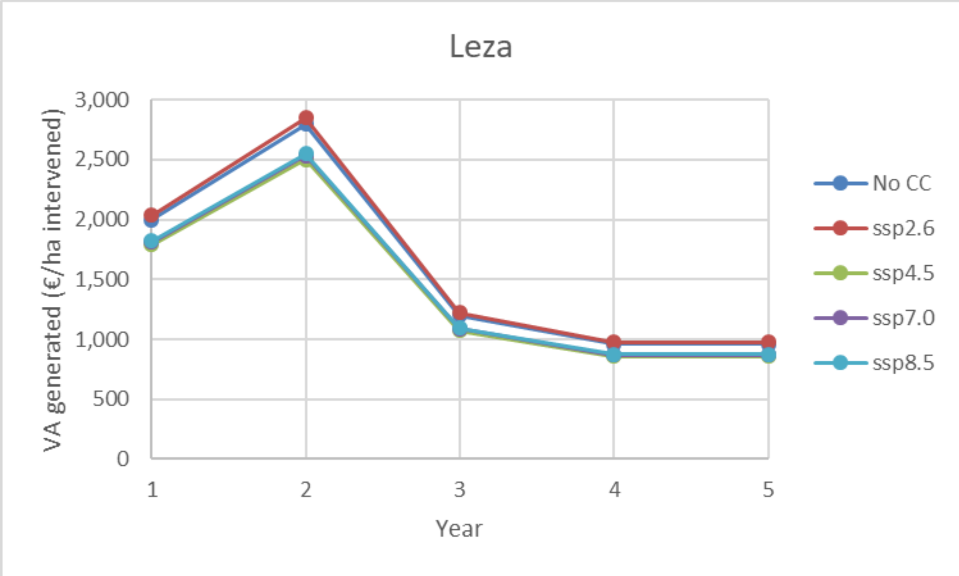

Figure 20. VA generated by the increase of water resources in Leza

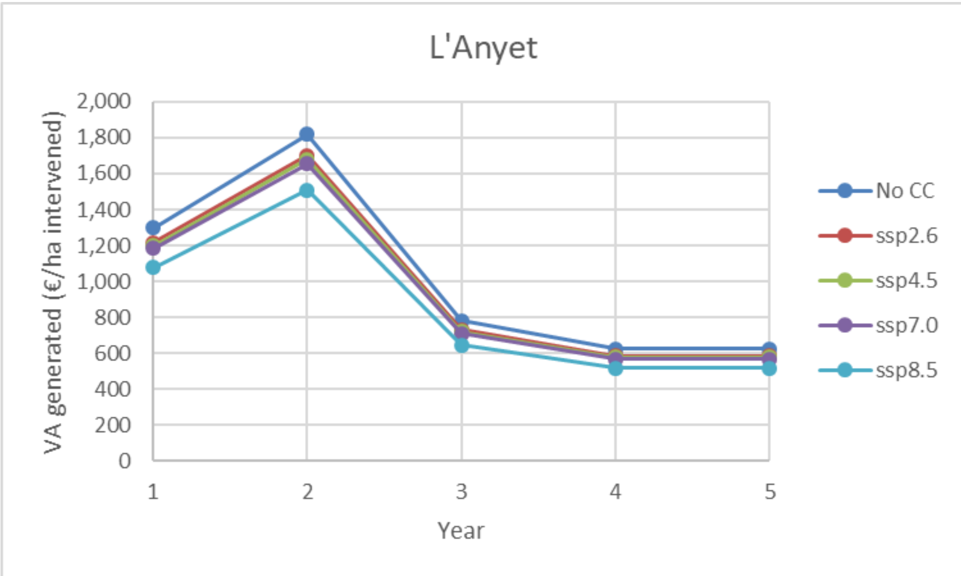

Figure 21. VA generated by the increase of water resources in L'Anyet

Scenario	Aísa (Aragon)	Leza (La Rioja)	L'Anyet (Catalonia)
No CC	-37.87 €	7,529.08 €	4,891.98 €
ssp2.6	51.29 €	7,673.00 €	4,580.02 €
ssp4.5	39.28 €	6,732.61 €	4,518.67 €
ssp7.0	146.04 €	6,824.58 €	4,454.94 €
ssp8.5	199.16 €	6,861.89 €	4,056.45 €

Table 18. Net Present Value of benefits from increased water availability (euros per hectare)

For the scenario without climate change Figure 20 shows that the interventions in Aísa would result in a loss of VA. In contrast, in those scenarios that considered the effects of climate change on the provision of water resources, the generated VA is positive and is in the range of 13.61 – 52.85 €/ha in the first year after the clearing and thinning actions, and between 19.06 – 74.00 €/ha in the second year. From the third year onwards VA values are still positive but decrease. Depending on the climate change scenario the net present value over the time horizon of 5 years is between -37.87 – 199.16 €/ha (see Table 18). We can compare these benefits with the costs of adaptation measures. The recovery of pastures through the clearing of 445 ha of shrubland has a cost of 434.27 €/ha at 2021 prices, and the clearing, pruning and thinning of 2,095 ha of coniferous forest a cost that ranges from 1,141 to 2,213 €/ha. Thus, the cost of the work will be between 1,017 and 1,901 €/ha. Therefore, the return on the intervention is between approximately 2% and 19.6% of the investment, i.e., for each euro invested, between 0.02 and 0.19 euros are recovered from the increase in water resources. This analysis suggests that from an economic point of view the modelled actions are not sufficient to provide a notable ecosystem service in terms of water provision. One possible explanation is the small surface area that can be cleared, or that a thinning of 50% of the coniferous forest cover is not sufficient. The high rainfall in the region, which might result in a smaller difference between management and non-management, is another plausible explanation.

On the other hand, for the case of the no climate change scenario the net present value of the increase in production (in terms of VA) generated by the clearing of 2,760 ha of shrub in the Leza valley amounts to 7,529 €/ha. When climate change is considered the increase in the VA is in the range of 7,632.61 – 7,673 €/ha (Table 18). These values are much higher than the cost of the adaptation measures, which indicates that the social benefit obtained from the increase in water resources is positive, even without taking into account additional ecosystem services that the forest may provide.

The results for the l'Anyet basin are similar to those of the Leza valley. The net present value when climate change is not taken into account is almost 4,900 €/ha. The benefits obtained are slightly lower for the climate change scenarios analysed (4,056.45 – 4,891.98 €/ha), but still higher than the cost of clearing and thinning.

In addition to the net present value of the measures, the cost of the water generated by these interventions has been calculated. Table 19 presents a summary of the results.

	Aísa (Aragon)	Leza (La Rioja)	L'Anyet (Catalonia)
Hectares intervened	445 shrub 2,095 reduction (*Pinus*)	2760 shrub clearing	326 abandoned fields recovery 1,218 thinning (*Quercus*)
Cost of clearing	193,250 €	1,198,626 €	141,852 €
Cost of forest management	2,390,395 – 4,636,235 €		1,389,467 – 2,694,908 €
Total cost	2,583,645 – 4,829,485 €	1,198,626 €	1,531,320 – 2,836,762 €
Cost per m^3 of water exported (No CC)	-	0.06 €	0.23 – 0.42 €
Cost per m^3 of water exported (ssp2.6)	22.09 – 41.29 €	0.06 €	0.24 – 0.45 €
Cost per m^3 of water exported (ssp4.5)	28.85 – 53.92€	0.07 €	0.24 – 0.45 €
Cost per m^3 of water exported (ssp7.0)	7.76 – 14.50€	0.07 €	0.25 – 0.46 €
Cost per m^3 of water exported (ssp8.5)	5.69 – 10.63€	0.07 €	0.27 – 0.50 €

Table 18. Calculation of the cost of exported water

Table 19 shows that the costs of water provision derived from the actions in Leza are 0.06 €/m^3 (0.07 €/m^3 in the scenarios that contemplate the change in climate conditions), while those of l'Anyet are between 0.23 and 0.42 €/m^3 (0.24 – 0.50 €/m^3 with climate change). As noted above, the lowest efficiency of the measure is observed at the Aísa site, where the costs of water provision are very high.

4.3. Discussion

This section provides an estimate of the economic value of the additional water resources generated by agricultural and forestry management actions in the mid-mountain area. The results show high differences that depend on the location and the actions proposed. They also suggest that certain adaptation measures can be very positive for the provision of essential ecosystem services in areas that are expected to suffer the negative effects of climate change. The employed model excludes some factors that could even accentuate the results. For example, the structure of the economy is assumed to be fixed, so that increases in water availability have been implemented in the different agricultural sectors following the current Spanish production structure (average of the period 2015-2019). But Spain is one of the most water-scarce and drought-prone areas in Europe, and in the near future the current economic structure could be compromised due to the imperative need to reduce irrigation demands to the level of available resources. In this context, greater water availability may help to alleviate the need to change from highly water demanding to lowly water demanding crops that have lower added value. Sensitivity analyses carried out considering the production structure in years of extreme drought (such as 2006-2009) show that the benefits presented in this report could increase by up to 70%.

Finally, it should be noted that in a context of considerable water stress, demand measures must be combined with policies aimed at increasing resource supply. If we compare the cost of exported water in Leza and l'Anyet with the current cost of desalination (0.6 – 1 €/m^3), or the cost of wastewater treatment for reuse (0.45 €/m^3), the study suggests that nature-based solutions are a promising alternative to reduce pressure on water resources.

Both the obtained costs of providing water and the benefits in terms of VA increase are relevant insofar as they make it possible to evaluate land management policies in terms of their cost-effectiveness. Even so, the results must be taken with caution. It will be possible to improve the prediction of the additional water supply provided by climate change adaptation measures in the mid-mountain as a greater number of hydrological monitoring studies become available, more extensive in time, and with rigorous and verifiable results. In addition, the obtained results can be considered as indicative for the Spanish territory. The analysis has been carried out with a multiregional IO matrix, examining the effect on Spanish GDP because of the data feasibility, and to allow the analysis to be replicated in other mid-mountain areas. However, it could be adjusted to the specific conditions of each basin or sub-basin when updated economic information becomes available at the regional level.

5. Conclusions

The main objective of this report is to present the socioeconomic evaluation of climate change adaptation measures that were realized in the marginal areas of the mid-mountains considered in the LIFE MIDMACC project, such as recovery of pastures, forest management and the introduction and optimization of vineyards. The document focuses on those aspects that, as a consequence of climate change, may have major economic impact; specifically, on the effects of an increased availability of water derived from different intervention measures, the fixation of population in the territory, and forest fires.

The results show that management measures have the potential to increase ecosystem services and obtain a considerable economic return. In particular, forest clearing can contribute significantly to decrease the probability of a forest fire (between 67 and 77% in the area examined, La Rioja), thereby reducing the area of forest burned by 86.2%. Thus, the private costs avoided per burned hectare are estimated to be approximately €1,400. As regards the evolution of the population in areas where clearing has been carried out compared to control areas (without clearing), an effect on the population fixation in the territory is perceptible, however not entirely clear. With respect to control areas, there are slight increases in population to the historical cessation of the loss of inhabitants.

To generalize the results obtained, the report presents a program that has been developed by the authors in order to determine the optimal level of the extension of different intervention measures with different capacities to reduce the spread of forest fires. The results show that even with a low extension rate, the burned area can be substantially reduced. From the reduction of the burned area, the program calculates the benefits and combines them with the costs of the intervention measures. This cost benefit analysis allows obtaining the optimal extension of the different intervention measures.

On the other hand, forest management also generates positive effects through increased water availability, which leads to higher agricultural production and increased activity in the different economic sectors. Thus, the measures analyzed in Aísa (Aragon) yield modest increases in VA of the order of 51.29 to 199.16 €/ha in the case of climate change scenarios, while in the Leza valley (La Rioja) and in the l'Anyet basin (Catalonia) the benefits are more notable and are around 7,000 € and 4,500 €/ha respectively. If we add the benefits of the higher availability of water to the benefits from the reduction in forest fires, we can consider that the intervention measures are effective and provide economic benefits that offset the costs of intervention.

The usefulness of the defined indicators has been tested as part of the evaluation process. Their accuracy depends on the availability of field data on the interventions. In this sense, the generation of new biological and ecological information, as it has been done in the LIFE MIDMACC project, is key for obtaining more accurate socioeconomic results It improves the design of public policies for the adaptation to climate change in the Mediterranean shrubland.

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Annex 1

```
In[ ]:= ext = Join[Range@50 / 100.]; eff = (Range@11 - 1) / 10.; risk = Monitor[
              junta                                                    monitor

    Table[{eff⟦i⟧, ext⟦n⟧, Mean@Table[bar1 = RandomVariate[BernoulliDistribution[ext⟦n⟧],
    tabla                  media tabla       variable aleatoria distribución Bernoulli

          100]; bar2 = Flatten@Position[bar1, 1];
                       aplana  posición

       β = {Append[bar2, 101], Append[ConstantArray[eff⟦i⟧, Length@bar2], 1]}ᵀ;
            añade              añade  arreglo constante     longitud

       Total@Table[(β⟦j,1⟧ - 1) β⟦j,2⟧ ∏_{k=1}^{j-1} (1 - β⟦k,2⟧), {j, Length@β}], 999]},
       total tabla                                                 longitud

     {n, Length@ext}, {i, Length@eff}], {i, n}];
         longitud         longitud

In[ ]:= a = Floor@Prepend[100 - risk⟦All,All,3⟧, 100 eff]ᵀ;
            entero·· añade al principio

        b = Prepend[a, Prepend[Floor[100 ext], "extension/efficiency"]];
            añade al pri···  añade al··  entero inferior

        bᵀ // TableForm (* share saved from fire *)
              forma de tabla
```

Annex 2

The multiregional input-output model used for the economic analysis considers all the intermediate exchanges between industries, as well as the final demands of countries and sectors (consumption, investment, public expenditure and exports) and is based on a variation of Leontief's (1941) model (specifically, it uses the approximation proposed by Ghosh (1958).

Leontief's model (1941) allows us to analyze the impact of changes in final demand on the production of each sector. It represents the production of the world economy made up of i sectors and r countries as follows

$$\mathbf{x} = \mathbf{Ze} + \mathbf{ye} \qquad [1]$$

where $\mathbf{x} = (x_i^r)$ is the matrix rxi which denotes the value of production in a given period. Its elements, x_i^r, represent the total production of industry i in region r, $\mathbf{y} = (y_i^{rs})$ is the final demand matrix, where y_i^{rs} is the final demand for products of industry i in region r made by region s, and $[z_{ij}^{rs}]$ is the multi-regional matrix of intermediates. The elements z_{ij}^{rs} correspond to the volume of input from sector i in country r that is used in the production of output j in country s and $\mathbf{e}$ is a unit vector. Figures 22 and 23 present an outline of the uniregional and multiregional IO model, respectively.

If we define the technical coefficients as $\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1}$, where its elements $\mathrm{A}_{\mathrm{ij}}^{\mathrm{rs}}$ can be interpreted as the value of the inputs of sector i in region r needed for each euro of production of sector j in region s, and $\hat{\mathbf{x}}$ represents the matrix of production that has been diagonalized, equation [1] can be expressed as the inverse Leontief function, $\mathbf{L} = [\mathrm{L}_{\mathrm{ij}}^{\mathrm{rs}}]$:

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y} \leftrightarrow \mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{Ly}$$

where each component of $\mathbf{L}$, $\mathrm{L}_{\mathrm{ij}}^{\mathrm{rs}}$, indicates the production of sector i of country r directly and indirectly incorporated in each unit of final demand of industry j of country s.

To relate the changes in the productive factors of each sector with the production of the same sector and of the other sectors, we can use the model of Ghosh (1958). This model is based on the same data as the previous model, but changes the perspective by rotating the way the table is analyzed from rows to columns, and relating sectoral gross production to raw materials, that is, to a unit of value that enters the inter-industrial system. This is why it is known as a supply-side IO model.

Instead of dividing each column of the matrix of intermediates $\mathbf{Z}$ by the production of the sector associated to the column in question, the rows of $\mathbf{Z}$ are divided by the associated production, obtaining the matrix of allocation coefficients $\mathbf{B} = \hat{\mathbf{x}}^{-1}\mathbf{Z}$, where its elements b_{ij}^{rs} represent the distribution of the output of sector i of country r in the sectors j of country s that buy inputs from i. Thus,

$$\mathbf{x}' = \mathbf{e}'\mathbf{Z} + \mathbf{e}'\mathbf{v}',$$

with $\mathbf{v}' = [v_1, \dots, v_n]$, where the elements of $\mathbf{v}'$ correspond to the value added of each of the economic sectors. Substituting $\mathbf{Z}$ by its value $\mathbf{Z} = \hat{\mathbf{x}}\mathbf{B}$, and given that $\mathbf{e}'\hat{\mathbf{x}} = \mathbf{x}'$ we get

$$\mathbf{x}' = \mathbf{e}'\hat{\mathbf{x}}\mathbf{B} + \mathbf{e}\mathbf{v}' = \mathbf{x}'\mathbf{B} + \mathbf{v}'$$

Leading to,

$$\mathbf{x}' = \mathbf{v}'(\mathbf{I} - \mathbf{B})^{-1} = \mathbf{v}'\mathbf{G}$$

where $\mathbf{G} = (\mathbf{I} - \mathbf{B})^{-1}$. Matrix $\mathbf{G}$ is known as the inverse matrix of output, and its elements g_{ij}^{rs} can be interpreted as the total value of output produced in sector j of country s per unit of primary input in sector i in country r.

From this model it is possible to find the impact that a change in the value added of a sector causes to the rest of the economy, that is, to the intermediate and final outputs. These changes would be defined by

$$\Delta\mathbf{x}' = (\Delta\mathbf{v}')\mathbf{G}$$

	Industry 1	...	Industry j	...	Industry n	Final demand	Total output
Industry 1	z_{11}					y_1	x_1
...							
Industry i			z_{ij}			y_i	x_i
...							
Industry n					z_{nn}	y_n	x_n
Value added	v_1		v_i		v_n		
Total output	x_1		x_i		x_n		

Figure 22. Diagram of an Input-Output model

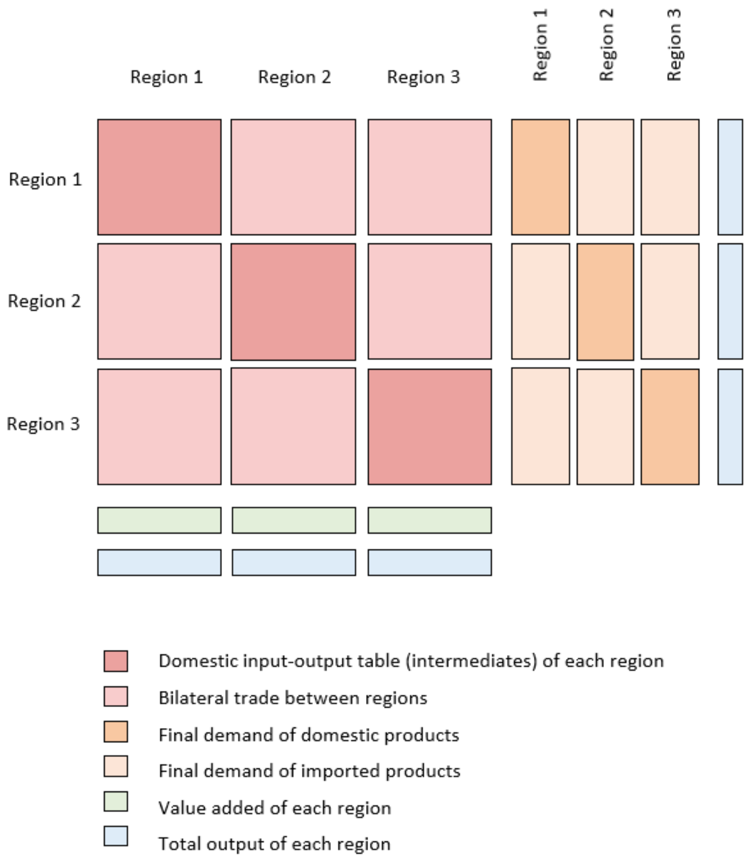

Figure 23. Diagram of a multiregional Input-Output model with 3 regions