HISTORIC LAND COVER CHANGE ASSESSMENT OF CHILEAN MEDITERRANEAN COAST: DID FOREST PLANTATIONS REALLY CAUSED FRAGMENTATION?

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ABSTRACT:

Currently, the Mediterranean coast of Chile has large areas of commercial pine and eucalyptus plantations. Several authors have reported habitat loss and fragmentation of the original "Maulino" native forest due to the expansion of plantations. However, in the Maule coast took place a previous process that affected the native forest. This is the extensive use of forestlands with a moderate slope for the cultivation of wheat. The peak of this process occurred in the second half of the 19th century and meant a great degradation of the soil in the area. In this work, we first look for whether the overexploitation of wheat is the primary cause of the fragmentation of the Maulino forest in the study area. Secondly, we wanted to determine what proportion of the area currently occupied by plantations was previously used for growing wheat. First, using the community of Constitución as a representative area of the central coast we use Species Distribution Modelling to identify the potential original extent of the Maulino forest. Secondly, we created a spatial model to estimate the extension of wheat production using historical data. Finally, we used Landsat-8 images to assess the actual extension of forest plantation. By comparing the three former results, we were able to quantify the effects of wheat production and forest plantation separately, for the first time. The results indicate that 41% of the original native forest was first affected by wheat production and that only 34 % was later replaced by forest plantations. Therefore, the rest of the plantations were installed in places where the forest had previously been cut down for use in wheat production. The main cause of deforestation and forest fragmentation in this landscape was originally the wheat extensive production boosted by the gold rush in California and Australia. Forest commercial plantations further augmented the Maulino forest fragmentation process by significantly reducing its mean patch size and increasing the number of patches.

1. INTRODUCTION

1.1 A brief history of Maule Region Coast

The coastal area of the Maule Region, in Chile, has undergone a series of transformations since the arrival of the Spaniards in this territory. The port and city of Constitución were founded in 1793 to function as the main outlet for products from the Maule Valley to Santiago, Peru and Europe (Memoria Chilena, 2022). Due to the lack of adequate roads for the land transport of goods, the main access route, from the valley to the port, was the Maule River, navigable from the regional capital Talca and the axis of supply for the entire Maule River Basin.

Wheat is a species introduced by the Spanish to Chile during the first years of the Conquest. As wheat is a crop that grows in winter and blooms and matures in spring, it adapted very well to the country's temperate Mediterranean climate, with rains concentrated in winter, achieving high yields, even tripling the yields of more tropical countries. Towards the end of the 17th Century, the central zone of the country increased its wheat area to supply the demand for wheat and flour of the Viceroyalty of Lima, which had been devastated by the 1687 earthquake and by the rust attack (dust-type fungus) that affected its wheat production (Montaldo, 2004). In this period, wheat production was concentrated in the surroundings of Santiago as well as in the surroundings of Talcahuano (Bauer, 1970).

The discovery of gold in California and Australia in the mid-nineteenth century, the so-called "gold rush", completely changed the structure of the markets available to Chilean agriculture. The Peruvian market had been closed after independence and its subsequent reopening was burdened with onerous tariffs for wheat exports. Farmers saw two new markets open up for the massive export of wheat and flour. In this way, the brief wheat cycles of California (1848-1853) and Australia (1850-1857) had a profound impact on the Chilean national economy, providing resources that allowed a certain modernization of rural life. However, the high production costs derived from inefficient technologies and labour systems made it impossible to compete in the medium and long term to maintain these markets. The roads were scarce and precarious, dozens of mules were used to transport the grains to the ports, taking several days, increasing cost production. Therefore, districts such as Rancagua, Colchagua and Talca were dedicated to the extensive exploitation of grasslands and only occasionally to grain production.

Towards the year 1850 the production of wheat was carried out near the ports that allowed its easy exit by sea or in the vicinity of the mills (Schneider, 1904). During the colony and until 1840, Chile exported an average of 135,000 qqm of wheat/year, which corresponded to 13% of national production. Table 1 shows the evolution of wheat production and the impact of the "gold rush"

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from California and Australia on national production and the Maule Valley, in particular.

Five-year period	Total Prod. (qqm)	Total Sup. (ha)	Maule (ha)
1841-45	12,25,000	122,500	12,250
1846-50	14,450,00	144,500	14,450
1851-55	1,715,000	171,500	54,880
1856-60	1,791,000	179,100	75,222
1861-65	2,335,000	233,500	98,070
1866-70	3,030,000	303,000	99,990
1871-75	3,374,000	337,400	111,342
1876-80	3,055,000	305,500	3,971

Table 1. Mean yearly production of wheat in Chile and Maule Valley (from Bauer, 1975). 1 quintal (qqm) = 100 kg.

This agricultural expansion associated to wheat production, as one of the main drivers, caused a severe deterioration of native vegetation and soils. By the mid-20th century, Maule, Ñuble and Biobío regions had moderate to high levels of erosion. Maule and Concepción, had more than 68% of their area eroded, especially in the Coastal Range (IREN-CORFO, 1965). Trying to improve this situation, the government decided to promote afforestation using fast growing exotic species (Albert, 1909; Elizalde, 1970). As result, *Pinus radiata* ended up being the main species because of a combination of a fast growth rate and high-quality wood (Camus, 2006).

Nowadays, Chile has close to 3 million hectares of forest plantations with exotic species, where *Pinus radiata* D. Don covers the largest extent. These are concentrated in the coastal communes between the Maule and the Araucanía Region and are all harvested through clearcutting. Forest plantations are located mainly in the coastal mountain range. During the last decades, this region has experienced strong changes in the configuration of the landscape, mainly associated with the expansion of plantations (Echeverria et al., 2006).

The Maulino forest, whose dominant species is *Nothofagus glauca*, a.k.a. "hualo", corresponds to the natural vegetation of the study area. Various studies report that this forest has been deforested and fragmented (Grez et al., 1997) with a reduction in the original forest area of 67% between 1975 and 2000 (Echeverria et al., 2006). However, none of these studies has explicitly considered the effects that agricultural overproduction of wheat had on the Maulino forest and it is common to indicate *Pinus radiata* plantations as the main cause of the fragmentation of native forests.

Considering the figures in table 1, the maximum production in the Maule Valley occurred in the five-year period 1871-1895, where 111,342 hectares per year were dedicated to wheat production. To arrive at these figures, data from Bauer (1975) were used, assuming an average yield of 10 qqm per hectare per year. Because wheat production requires at least one year of intercalated fallow, the amount of 222,864 hectares necessary to maintain the average production reported for this five-year period is reached. Where those lands were cultivated with wheat is one of the challenges to be address in this research.

Taking into consideration the above, we propose the following objectives: i) To evaluate whether the overexploitation of wheat is the primary cause of the fragmentation of the Maulino forest in the study area; ii) To determine what proportion of the area currently occupied by plantations was previously used for growing wheat.

2. METHODS

2.1 Study Area

This study was carried out in the coastal community of Constitución, Maule Region, in Central Chile (Figure 1). This commune of 134,000 hectares is dominated by forest plantations, mostly monocultures of *Pinus radiata* covering approximately 70% of its surface (CONAF-CONAMA-BIRF, 1999).

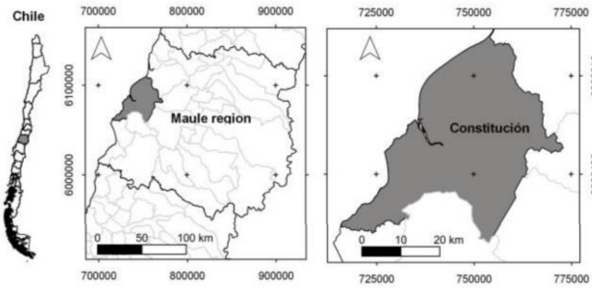

Figure 1. Study area.

2.2 Overall Approach

The following effects on the Maulino forest were evaluated:

i. Loss due to land use for wheat production and,
ii. Replacement by commercial plantations.
iii. Impact on Maulino forest fragmentation.

The first was performed in two stages, first, through species distribution modelling to obtain the potential distribution of the Maulino forest using the hualo as a *proxy*. Then, the surface that would have been used for the production of the cereal was estimated through spatial restrictions and geoprocessing. From the crossing of both, the estimated area of Maulino Forest affected by extensive wheat agriculture was obtained. Second, Landsat 8 images were classified to determine the current area occupied by plantations. Finally, all previous results were compared to assess all changes of interest and impact on fragmentation process. Methodological details are presented below.

2.3 Species distribution modelling

Maxent and random forest (RF) have proven to be two of the best performing methods for potential species distribution modelling (SDM) (Elith & Graham, 2009). We used R package dismo (Hijmans & Elith, 2013) for both algorithms to model hualo potential distribution. Primary, hualo occurrence data were gathered from GBIF public database (64 records, after data cleaning). We partitioned the occurrence locations at random in two subsamples; 80% of locations were used as a training dataset and the remaining 20% to test the resulting models (Marino et al., 2011). RF models were constructed growing 500 trees per iteration. We randomly chose 2000 background points throughout the study area (Lobo & Tognelli, 2011), but excluding sites with known records (Liu et al., 2013). To avoid them coinciding with occurrence locations, a radius of 1 km from each occurrence location was excluded, avoiding over prediction (Lobo & Tognelli, 2011).

2.4 Historic wheat production modelling

To model the geographic extent of historical wheat production around 1871-1875, we following the next steps:

a. Construction of a transportation cost raster to the port of Constitución based on the following equation, applied to each pixel of 100 x100 m:

$$Cost = (Dist_{River} * W_{dist\_port})^b$$

Where:

Cost = cost assign to each pixel

b = exponent equals 1, 1.5 and 2 if distance de port is less than 20 km, between 20 and 30 km or more, respectively.

$Dist_{River}$ = Distance (m) from each pixel to Maule river.

W_{dist_port} = Weighting based on the distance to the Port according to the following table:

W_{dist_port}	Distance to Port
0.5	< 10 km
0.6	10 – 20 km
0.7	20 – 30 km
0.8	30 – 40 km
0.9	40 – 50 km
1.0	> 50 km

Table 2. Weighted values W_{dist_port}

b. Elimination of pixels with slopes greater than 15 degrees or that correspond to unsupported land covers: wetlands, sands, bodies of water.
c. Subdivision of the resulting raster in zones of 100 pixels, vectorization of the same and assignment of the average cost value of the zone (zonal statistics).
d. Sorting polygons according to the average cost, from the lowest to the highest, and select them until the added area is as close to 222,864 hectares as possible.
e. The selected polygons make up the geographic space affected by wheat production according to the model used.

2.5 Satellite image processing

We produced a land cover map, in raster format, for 2015. We applied supervised classification using the Google Earth Engine (GEE) platform (Woodcock et al., 2008). Surface Reflectance Tier 1 of Landsat-8 images were used for the classification. Collection Tier 1 are atmospheric corrected and radiometrically calibrated, being suitable for a time series analysis (USGS 2019). All image collections were filtered by date (January 1 to December 31), by location (polygon of the study area), and by percentage of cloudiness of the scene (<5%). Subsequently, the relief effect was reduced by applying a topographic correction using the approach proposed by (Soenen et al., 2005). As there is not a free public topographic data in Chile, NASA SRTM Digital Elevation Model (Farr et al., 2007) was used for this purpose.
Our approach to classify land cover classes followed the methods proposed by (Zhao et al., 2016), explicitly developed for Chile. Complementarily, all methods to identify land cover are fully described in (Cortés et al., 2020).

The following land cover classes were used in this study: PI: pine plantation, EU: eucalyptus plantation, HT: harvested patch, NF: native forest (deciduous forest where the dominant species is Nothofagus glauca), SC: scrublands (areas with > 50% cover of short-statured trees), WT: water body, UB: urban settlement, SA: sands, AG: agriculture or prairie lands, BR: burned patch.

2.6 Geospatial change analysis

Finally, the layers of maulino forest, wheat and plantations were cut using the administrative limits of the Constitución commune, to then obtain the surfaces in hectares. To calculate the area of Maulino forest replaced by wheat cultivation, the intersection geoprocess between both layers was performed. The same procedure was performed between the wheat and plantation layers.

2.7 Fragmentation analysis

To evaluate the fragmentation process on Maulino forest, the Patch Number (NP) and Mean Patch Area (AREA_MN) were calculated using Fragstat (McGarigal et al., 2002). There are many ladnscape metrics that can be used for this purpose but, for the sake of simplicity, we selected the two most obvious ones. They also have a straight forward interpretation. These metrics were calculated for three historic moments of Maulino forest distribution: i) Original distribution, ii) after wheat production impact, and iii) including forest plantations impact.

3. RESULTS

3.1 Bosque Maulino original distribution

To model the original distribution of the hualo we used the entire geographic range of the species. Then the information for the study area was extracted. Both RF and MaxEnt yielded results with high AUC values, both above 0.95, and significant correlations (table 3).

We used max TPR+TNR values as thresholds to obtain habitat/non-habitat maps from both models. Finally, the intersection of both was considered as the most probable habitat. In other words, for a pixel to be taken as habitat, it had to be so in both models separately.

Model metric	RF	MaxEnt
AUC	0.9708	0.9683
cor	0.7618	0.6972
max TPR+TNR	0.2098	0.4642

Table 3. SDM metrics for RF and MaxEnt.

The final map for the potential distribution of Maulino Forest is shown in figure 3 (upper-left). This forest type covered around 60% of the community of Constitución. The results fulfil standard requirements of fitness but they can be improve in the future. Nevertheless, some improvements can be incorporated in future modelling efforts:

i. Increase spatial resolution using local climate data,
ii. To gather some more occurrence points.

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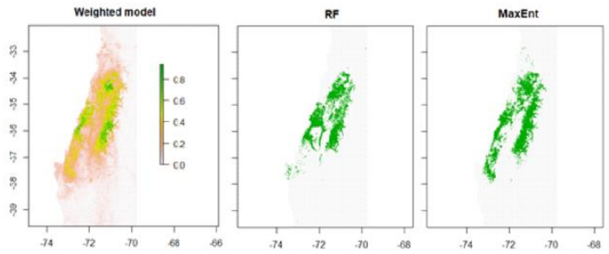

Figure 2. SDM ensemble model (left) and habitat map from RF model (centre) and MaxEnt (right).

3.2 Wheat cultivation effects on Bosque Maulino

Of the total Maulino Forest obtained via SDM, it was estimated that 41% (32,197 ha) was cut down for wheat cultivation (table 4). From maps in figure 3, it is evident the overlap between the original Bosque Maulino original distribution and the area occupied by the estimated wheat production. In our model, one of the more important steps is the building of the cost raster, which is use to sort polygons that are lately selected to be part of the wheat historic cultivated area.

The function to estimate the cost can make the results vary and a further sensitivity analysis should be applied in future research. We believe that the results are sound and close to the historic reality where the quality of soil and other environmental variables did not matter as much as distance and travelling cost.

3.3 Forest plantation effects on Bosque Maulino

In the supervised classification process, we used a total of 36 landsat-8 images and 2628 ground control points. The classified images have a general accuracy of 0.93 and a kappa index of 0.92. Table 4 shows the results of the spatial analysis to calculate the amount of area covered by Maulino Forest, historical wheat cultivation and current plantations. If there were no human influence at all, 60.3 % of Constitución community would be cover by Maulino forest.

Land cover	Area (ha)	% Constitución
Forest plantation	78,744	58.8
Maulino Forest	80,773	60.3
Wheat	44,145	32.9

Table 4. Areas of Maulino forest (potential original), plantation (actual) and wheat (1871-75) in the study area.

Table 5 shows the changes from Maulino Forest to wheat, from wheat to plantation, and from Maulino Forest to plantation. It is evident that, according to the assumptions used in this study, the greatest impact on the loss and fragmentation of the Maulino Forest was caused by the historical cultivation of wheat.

Change	Area (ha)	% MF
MF to Wheat	32,197	40 %
Wheat to PL	30,754	-
MF to PL	27,810	34 %

Table 5. Historic transformations from the interested land covers in the study area. MF = Maulino Forest. PL = Plantation.

Forest plantations are currently installed where there was previously wheat cultivation (31%), replacing native forests (28%) and transforming other land covers. The replacement of the Maulino Forest also involves other transformations, according to the resulting figures. These transformations have been to enable urban land, modern agriculture, network of roads, among the main ones.

3.4 Fragmentation

The three landscape metrics were obtained for the three historic moments of Maulino forest: original distribution, after wheat crops effects and after plantations expanse process. They evidence and intensive process of fragmentation (table 6). Originally, there were two main big patches of Maulino forest, South and North from Maule river. By the end of the XIX century, after the main effect of the gold rush, this number increase to 336 patches associated to a decreasing in mean patch size from ~ 40.000 to 145 ha. Then, forest plantation augmented the process by further reducing the patch mean size to only 7 ha.

Maulino forest	NP	AREA_MN
Original	2	40,417
After wheat effect	336	145
After plantation expanse	2984	7

Table 6. Maulino forest landscape metrics for three historic moments: Patch Number (NP) and Mean Patch Area in hectares.

3.5 Final remarks

The conceptualization of the calculation model for the cost raster must be carefully evaluated. We assumed that in the late 19th century, the cost of travelling overland was the biggest constraint. At that time, the routes to the capital, Santiago, were not well implemented and the train had not yet been built. For this reason, the fluvial route through the Maule River was the cheapest and safest to be able to export agricultural products. We assume a cost function proportional to the distance to the river, corrected for the distance to the port of Constitución. In addition, since trips of more than 1 day by cart or mule were very expensive, it was assumed that distances greater than 20 km meant costs that increased exponentially with distance.

Given that at the time the dominant rotation was wheat-fallow, it was considered that an area similar to that of wheat was fallow. This very common practice of Mediterranean zones, consists of leaving the soil prepared (plowed and raked) for a period ranging from six to twelve months. This practice has several advantages, one of them is that time is saved in the preparation of the soil for the next planting. However, it has disadvantages such as leaving the soil exposed to the action of rain.

On the other hand, it was assumed that it could be cultivated on slopes of up to 20 degrees, which is unthinkable today but perfectly feasible in those times and in an area without much flat land. In the future, we would like to have some field checkpoints for places that were cultivated with wheat in the past. This would have to be corroborated with field data by interviewing older people who remember where there was wheat. Another aspect to consider is that towards the South, there were other ports, through which agricultural products also left. This could limit the extension of the cost model in that geographical direction.

We believe that this approach is innovative and that it opens the door to continue increasing the precision and accuracy of the results as new data and models are incorporated.

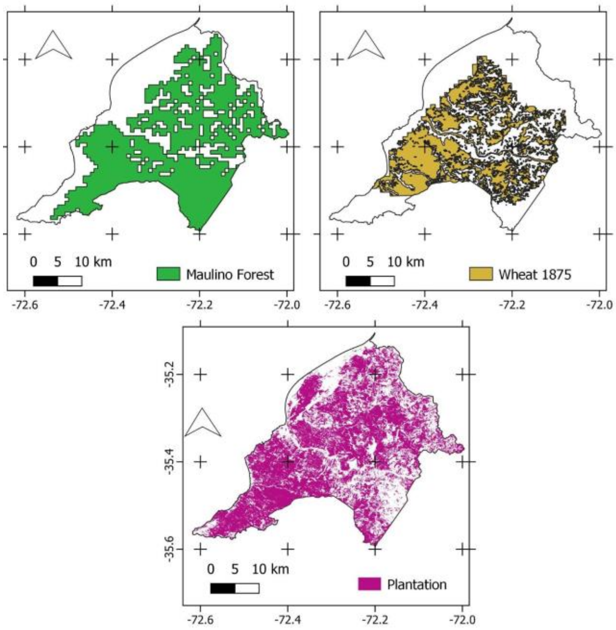

Figure 3. Maps of the original Maulino forest distribution (upper-left), extent of the wheat production in 1871-1875 (upper-right) and present extent of the forest plantations (bottom).

4. CONCLUSIONS

Combining techniques for modelling the distribution of species, agricultural production and image analysis, it was Possible to reconstitute the history of the last 150 years of the landscape under study.

Under the assumptions used, it follows that the overexploitation of wheat is the primary cause of the fragmentation of the Maulino forest in the study area. We also determined that a significant proportion of the area currently occupied by plantations was previously used for growing wheat. The plantations could have improved the structural and functional connectivity affected by overexploitation with wheat. Nevertheless, forest commercial plantations further augmented the Maulino forest fragmentation process by significantly reducing its mean patch size and increasing the number of patches.

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