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Spatial Patterns of Productivity and Human Development Potentials for *Pinus pinea* L.

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Abstract: *Pinus pinea* (stone pine), a Mediterranean species, is valued for its highly nutritious pine nuts and its ability to adapt to different environmental conditions. The species has been increasingly planted in Chile, where its main ecological requirements are met across a vast area. However, new plantations are established without considering social dimensions. Policymakers can regulate private decisions on tree planting through the appropriate design of economic incentives to foster social well-being. The objective of this work was to describe spatial patterns of potential areas for the cultivation of the exotic nut-bearing conifer *P. pinea* in central Chile and the possible correlation of those patterns with human development indices. Spatial data layers of the municipality development index (MDI), elevation, edaphoclimatic variables, and stone pine nut's productive potential were overlapped at the municipality scale along 1225 km in central Chile. A spatial principal component analysis (sPCA) was used to integrate multiple dimensions, summarizing covariation structures, and identifying spatial patterns in the study area. Key results showed that spatial patterns of the potential productive index (PPI) were strongly regulated by the spatial pattern of climate and soil variables, whereas the spatial pattern of MDI showed a cryptic pattern and that the three dimensions of MDI—welfare, economy, and education—showed a different spatial movement, especially education and welfare. The results allow us to recommend that public policies boost municipality development through the promotion of *P. pinea* plantations and should target areas with a high productive potential and low MDI to generate socio-economic improvements. These findings are useful for the strategic spatial planning of the species cropping in Chile.

Keywords: multiple-use systems; pine nut production; stone pine cropping impact; human development index

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1. Introduction

Climate change is one of the most serious present challenges, characterized by rising global temperatures, extreme heat exposure, changes in precipitation regimes, reduction of winter chill, and an increased frequency and intensity of extreme weather events. These alterations are expected to be harsher in the upcoming decades and to reduce the quality and yield of crops [1–3]. In order to sustain crop production, support local communities in terms of income generation and avoidance of migration, and bolster food security at the local, national, and global scales, resilient crops and technological solutions need to be identified [4].

Therefore, climate-resilient crops should be cultivated, especially in rural agricultural communities, to ensure household income and achieve an adequate daily intake of calories and a balanced nutrition [5]. Plantations of *Pinus pinea* L., a drought-resistant species [6], contribute to food production because the species' highly priced edible pine nuts are among the most expensive nuts in the world [7,8]. Indeed, pine nuts have a unique nutritional profile, including high-quality fats, proteins, vitamins, minerals, and bioactive compounds [9,10], and could potentially be used for plant-based alternatives in the food industry [11], including functional foods [12]. The species also provides several environmental services, such as soil and watershed protection, dune control, soil recovery, and erosion control. Pine nut processing also generates a high volume of biomass as a by-product [13], which can be used for different purposes.

P. pinea plays an important role in the economy and landscape of many Mediterranean areas [14]. This species is currently planted in several countries given its attractive socio-economic benefits. *P. pinea* forests have been reported to be crucial in many rural and smallholder communities in the speciesnative habitat. Indeed, they provide food resources and cash income at the farm-household level in several European countries [14], Turkey [15], and Lebanon [16]. In Lebanon, it is recognized as *white gold*, and provides the highest gross revenue from forest goods [17]. These benefits have also been reported in non-native habitats such as Tunisia [18], where the species plays a key role in rural development.

The species has been increasingly planted in the Southern Hemisphere because its main ecological requirements are met across a vast territory and because it can be cropped in pure plantations or in agroforestry and silvopastoral systems [19–21]. However, new plantations are established without considering social dimensions, since land use decisions are made by private landowners who seek the maximum possible land rent [22]. The expected income depends on the site productivity, which is determined by climate conditions and soil characteristics, by the features of the species to be cultivated, and by the technology applied to the crop. Last, but not least, the income depends on market conditions, including the business environment and mid- and long-term economic expectations, given that these are tree crops with long-time horizons. Since land-use decisions by the private sector are made purely in line with profit maximization [22], the social dimension is then in the hands of policymakers, who would have the responsibility of articulating private landowners' decisions through the appropriate design of economic incentives in order to obtain maximum social well-being.

In Chile, the forest sector is based on industrial *P. radiata* and *Eucalyptus* spp. plantations run by a few big forest companies. Small and medium forest landowners and enterprises are faced with major barriers, namely economies of scale, technological gaps, and the need for farm-households to maintain an annual cash income for their sustenance [23], which prevent them from profiting from industrial forest plantations. For example, small farmers intending to plant do not have easy access to credit; because of the small land plot size, they cannot obtain an annual cash income and, therefore, they cannot rely only on timber harvest [24]; and they have higher production costs and access to lower levels of technology than large landowners and forestry companies. On the contrary, the production of *P. pinea* is an attractive option for small and medium farm-households because the high value of pine nuts yields high land rents, and, most importantly, as with the cultivation of fruit trees or annual crops, they can obtain annual cash income for their sustenance.

P. pinea has shown positive results in terms of growth and cone production [25] in Chile, where the areas suitable for the cultivation of the species have been estimated at over 4.8 million hectares [26]. Furthermore, important efforts have been made in this country to develop management techniques for pine nut production [27,28], with over 5000 hectares of new plantations having been established by private landowners since 2014.

Given the characteristics of the species, *P. pinea* plantations contribute to 9 of the 17 sustainable development goals [29]: no poverty (1), good health and well-being (3), decent work and economic growth (8), industry, innovation, and infrastructure (9), inequalities reduction (10), sustainable cities and communities (11), responsible consumption and production (12), climate action (13), and life on land (15).

The cultivation of *P. pinea* in disadvantaged poor rural areas can generate important benefits [30]. Benefits can be direct on the local economic development through the generation of income and jobs, and the development of the productive chain of cones or pine nuts. Benefits can also be indirect, through the purchase of other goods and services, which in turn boosts the economy. To develop a useful tool for public policy planning, [26] presented a first descriptive approach for the species. The authors linked cartographic information of potential areas for *P. pinea* cultivation to the Human Development Index [31] at the municipality level (a single administrative division that has corporate status and powers of self-government or jurisdiction as granted by national and regional laws to which it is subordinated). The resulting maps based on expert knowledge defined a priority ranking to sustain public policies.

Food security requires that crops are established in edaphoclimatic areas where high production is ensured. Therefore, productivity zoning reveals the economic feasibility of a given crop by zone. However, potential areas for production rarely incorporate the covariation of environmental variables with indicators of social development. For *P. pinea*, zoning of areas is usually performed according to the productive potential of the species, including variables such as tree growth and fruit production [25], and the analysis of spatial co-variability is also rarely applied.

This study aims to describe spatial data important for mapping the productive potential of *P. pinea* and human dimensions using an innovative spatial methodology, providing a tool to guide targeted afforestation policies. Thus, we established the following research questions on *P. pinea*: (i) is it feasible to reveal spatial patterns through a statistical method that considers spatial information directly as a component of the adjusted model, and (ii) based on the spatial information, is it possible to prioritize *P. pinea* plantations to boost the socio-economic level at the municipality scale?

2. Materials and Methods

2.1. Study Area and Scale

The study area includes a latitudinal gradient between 29.0° and 39.7° S and a longitudinal gradient between 73.9° and 69.8° W, totaling 18.6 million ha (24.5% of the country). The area includes 219 administrative municipalities in Chile, with an average of 84,700 ha each (Figure 1).

Figure 1. Study area depicting 219 municipality divisions in central-southern Chile. Centroids were used as coordinates to georeference each municipality. The grey area (lat 33.5° S) corresponds to the metropolitan area of Santiago, the capital city.

2.2. Databases

Following Avila et al. [26], and using field and satellite data, we refined several layers of information with the aim to map the productive potential of the species in Chile. Additionally, a municipality development index, which includes components of welfare, economy, and education of the local population, was calculated using a multivariate and multidimensional analysis [32]. These authors built a municipality development index (MDI) to describe the level of economic development of Chilean municipalities. The human dimension index MDI combines variables related to three dimensions: "health and social welfare", "economy and resources", and "education", which in turn are built on several relevant variables at the municipality level (Table 1).

The values of the three dimensions of the MDI were assigned to each municipality using a Geographic Information System (GIS). The values for economy, welfare, and education were grouped into four classes (distribution quartiles) (Figure 2a–c), while the MDI values were classified into five categories: Low: 0–0.28; Medium-Low: 0.29–0.38; Medium: 0.39–0.49; Medium-High: 0.50–0.60; and High: >0.60 (Figure 2d). Categories are depicted in the maps with a color of increasing intensity as the variable value increases. A georeferenced database was generated at the municipality scale with site and environmental variables. The site variables were soil texture (percentage of clay content, ranging from 13% to 39%) (Figure 3a) and available water capacity (field capacity minus permanent wilting point, AWC). The environmental variables were elevation (m asl, meters above the sea level, ranging from 0 to 3220) (Figure 3b), obtained from a digital elevation model, and annual cumulative rainfall (PP) (ranging from 60 to 3690 mm) (Figure 3c).

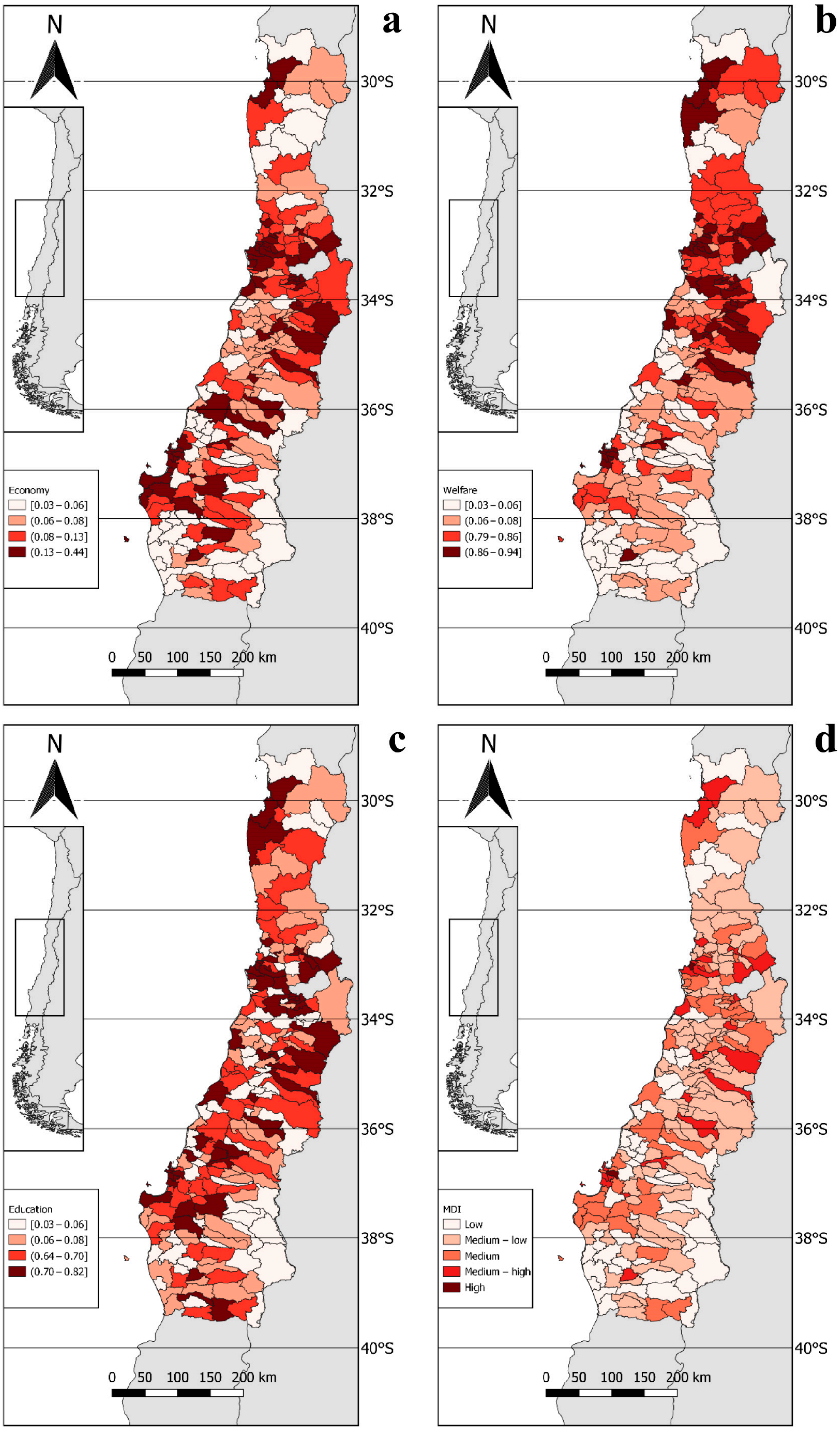

Figure 2. Spatial pattern of the municipality development index (MDI) (**d**) and its three main components: economy (**a**), welfare (**b**), and education (**c**). MDI categories as defined by Hernández et al. [32]. Categories correspond to distribution quartiles.

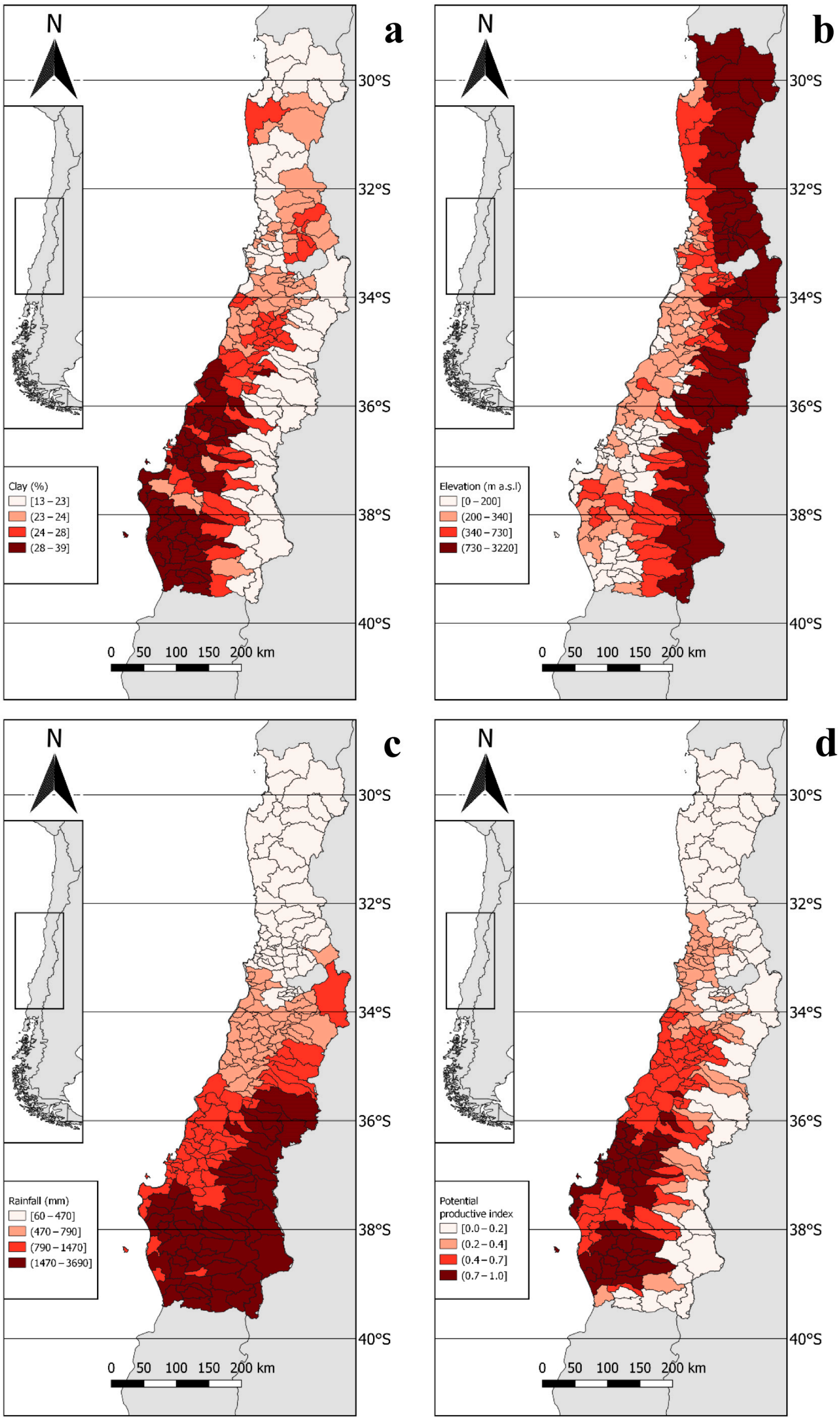

Figure 3. Spatial pattern of soil clay content (**a**), elevation (**b**), rainfall (**c**), and potential productive index (PPI) for *P. pinea* (**d**). Categories correspond to distribution quartiles. PPI varies between 0 (municipality unsuitable for production) and 1 (municipality with high productive potential); values close to 0.25 mean municipalities with potential for plantations focused on environmental protection, and values from 0.25 to 1 correspond to municipalities with an increasing cone production aptitude.

Table 1. Dimensions and variables considered to calculate the municipality development index (MDI).

Dimension	Variable	Description	Year
Health and social welfare	Basic services	Percentage of households without basic services	2017
	Poverty	Percentage of households in poverty	2017
	Drinking water	Percentage of drinking water coverage in the municipality	2018
	Potential Years of Life Lost	Potential Years of Life Lost (PYLL)	2014
Economy and resources	Age dependency	Age dependency (inactive population >65 years that depends on the economically active population)	2017
	Permanent own income	Permanent own income of the municipality	2018
	Internet	Landline internet subscription per inhabitant	2018
	Companies	Number of companies per inhabitant	2017
Education	National Education Quality Test (SIMCE) for Spanish Language	Average score on Spanish language (SIMCE test) of eighth-grade students	2017
	SIMCE for mathematics	Average score on mathematics (SIMCE test) of eighth-grade students	2017
	Preschool enrollment	Percentage of 4- and 5-year-old children enrolled in preschool education	2018
	Student enrollment in secondary education	Enrollment of 14- to 17-year-old students in secondary school	2018
	The University Selection Test (Spanish: Prueba de Selección Universitaria or PSU) was a standardized test used for college admissions in Chile.	Average percentage of students with PSU scores over 450 points (on a 150 to 850 scale) in municipal schools, subsidized and private	2018

Source: Hernández et al. [32].

Using mostly *P. pinea* climatic requirements, mainly rainfall and temperatures, Avila et al. [26] defined potential productive areas, which were classified into five categories, and assigned a score of productive suitability, with a score of 0 corresponding to the land area “unsuitable for production”, a score of 1 to the area “suitable for environmental protection”, a score of 2 to the area of “low productive potential”, a score of 3 to the area of “medium productive potential”, and a score of 4 to the area of “high productive potential”. At the municipality level, a weighted productive potential index (PPI) was calculated; the share of land of each category was multiplied by its score and then the sum of shares of land in each category was divided by the municipality area. The PPI was then obtained as follows:

$$PPI = \frac{0 \times unsuitable + 1 \times protection + 2 \times low + 3 \times medium + 4 \times high}{(unsuitable + protection + low + medium + high) \times 4} \quad (1)$$

PPI ranges between 0 and 1, as follows: 0: municipality unsuitable for production, 1: municipality with high productive potential; values close to 0.25: municipality with potential for *P. pinea* plantation with purpose of environmental protection, and values from 0.25 to 1 indicate a municipality with increasing degree of cone productive potential.

2.3. Statistical Analyses

A spatial principal component analysis (sPCA) [33] was used to analyze the PPI, MDI, elevation, PP, soil sand and clay content (%), AWC, welfare, education, and economy. Using sPCA, we generated linear combinations of the original variables, taking into account the spatial location of each municipality and the value of the variables in neighboring municipalities, to identify spatial autocorrelation. A principal component analysis with spatial restriction, MULTISPATI-PCA, was performed considering the inputs of the human dimensions of welfare (i.e., "health and social welfare"), economy (i.e., "economy and resources"), and "education", plus the human dimension index for each municipality (MDI). We also included site and environmental variables (elevation, AWC, clay content, PP, and PPI). MULTISPATI-PCA introduces a spatial weighting matrix to calculate spatial correlations among the original data [34]. Spatial autocorrelations are obtained using Moran's index, taking into account the network of neighboring observations of raw data. Neighbors can be defined using different connection networks. We established a maximum distance of 50 km to create neighborhoods consistent with the phenomena under study; this value was determined by considering municipality size. The MULTISPATI-PCA procedure was implemented using the library "ade4" [35] and "spdep" [36]. The statistical analyses were conducted using the software R [37]. The spatial principal components (sPCs) (generated synthetic variables) necessary for accounting for the cumulative variability percentage of at least 60% of the total variability were selected for further clustering; sPCs that significantly explained variability patterns were plotted using QGIS 3.22 at the municipality scale [38]. The sPCA was the selected statistical technique since we aimed to combine several dimensions in new variables to the map spatial variability of these synthetic variables. The sPCA is better than the classic PCA (alternative method) in the sense that the technique takes into consideration the spatial correlation of the original variables. Univariate measurements of spatial autocorrelation, such as Moran's I, are widely used, but extensions to the multivariate case (i.e., multi-variables) are rare. MULTISPATI is a multivariate spatial analysis based on Moran's I.

3. Results

The results indicate that the interpretation of the dataset's global variability can be performed by analyzing a few principal components, i.e., reducing problem dimensionality. sPC1 and sPC2 accounted for 36.6% and 20.6% of the total variance, respectively. Moreover, a significant and high spatial autocorrelation in these new variables was found. The Moran index for sPC1 and sPC2 was I = 0.86 and I = 0.54, respectively, indicating the presence of positive spatial autocorrelation in the first two principal components. However, a significant but negative spatial correlation was found in the last principal components sPC9 and sPC10. Thus, another type of spatial pattern exists in the original variables with high weight in the last principal components.

The variances and spatial autocorrelation coefficients (Moran index) of each significant synthetic variable (sPC), derived from MULTISPATI-PCA, as well as related eigenvectors and Pearson correlation coefficients of each original variable with each synthetic variable, are presented in the Supplementary Material (Tables S1 and S2). The elements in the eigenvector associated with a principal component are the weights of each original variable in the new synthetic one. The higher the weight (in absolute value), the higher the contribution of the variable to the explanation of variability.

The most determinant variables to describe data variability and positive spatial autocorrelation are environmental or ecological variables. The biplot of the first two sPCs (Figure 4) allowed us to observe that high values of AWC, PP, and clay content positively correlated with PPI. AWC, PP, clay content, and PPI were the variables with a higher positive correlation with sPC1. The new variable sPC2 was closely related to elevation, indicating that high PPI was related to lower elevation. Among social dimensions, education and economy were more related to MDI than welfare.

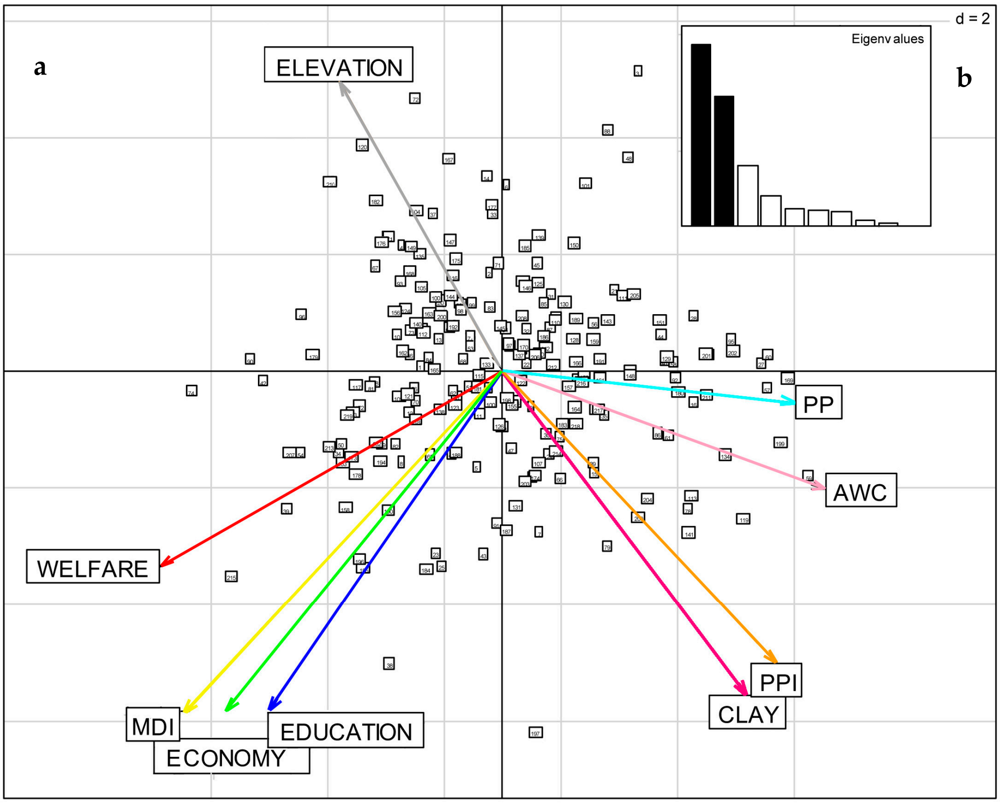

Figure 4. Spatial principal component analysis of environmental and social municipality data. Barplot of eigenvalues (**a**). Correlation between variables and principal components, and projections of municipalities on main axes (**b**). Different squares correspond to the studied municipalities of Chile.

The first sPC1, positively correlated to PPI, can be interpreted as a proxy for good site quality, and sPC2 means that at a higher elevation, the site quality is lower, which is consistent with a decreasing production potential. The negative correlation of sPC2 to the elevation can be related with the fact that sites at high elevations in Chile have snowy precipitation, which cancels out the positive effect of high AWC, as reflected by the negative coefficients for AWC and PP (Figure 5b).

The global spatial structure reflected by these first two sPCs is visualized in Figure 5a,b. In Figure 5a, the high *P. pinea* PPI (high values of sPC1) is located in the southern portion of the study area, showing a clear increasing gradient from north to south. In Figure 5b (sPC2), the spatial variability follows an elevation gradient, indicating that mountain range zones are less suitable for *P. pinea* cropping than areas with non-clayey soils, which have a higher clay content and more water availability.

As mentioned above, while the spatial autocorrelation in the first two sPCs (sPC 1 and sPC2) was positive, the spatial autocorrelation of the last two sPCs (sPC9 and sPC10) was also statistically significant but negative, suggesting another type of spatial pattern for the variables with higher weights on these principal components. Both, sPC9 and sPC10, were negatively and significantly correlated with MDI and the measured social dimensions, whereas the correlation with the environmental variables was marginal. sPC10 was positively and highly correlated with education but not with welfare. In municipalities where there is a high level of education, the level of welfare is lower. This can occur in municipalities with a dense urban population, like urban centers close to large cities, indicating higher levels of education than in rural municipalities, but not necessarily a better level of well-being (Figure 5d). Therefore, results reveal cryptic spatial patterns for

MDI, i.e., spatial patterns that are not associated with the highest total variation in the data [39]. Then, the municipality or group of municipalities with the highest values of MDI has neighboring municipalities with a different MDI category.

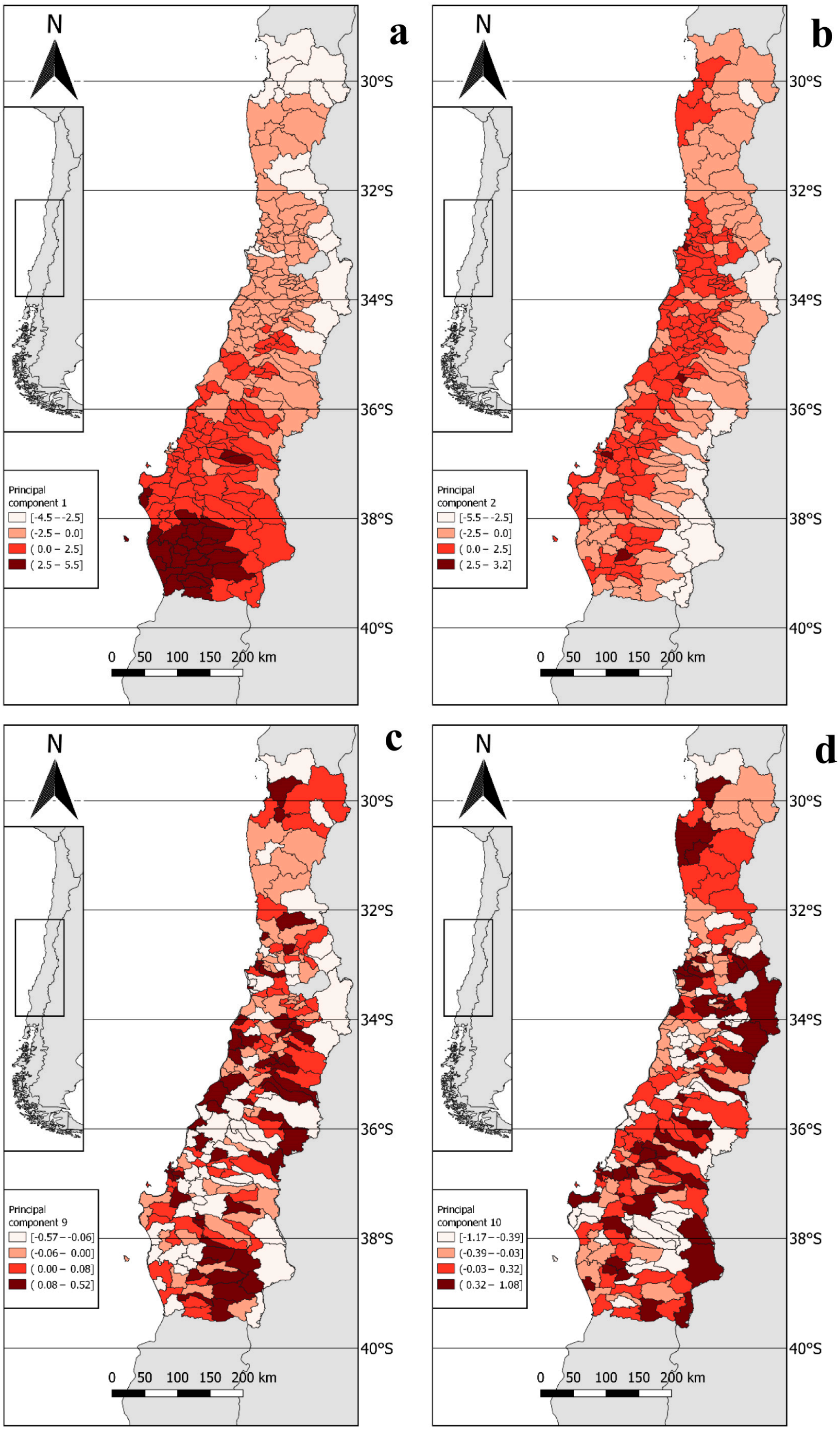

Figure 5. Spatial patterns of synthetic variables representing environmental dimensions (sPC1, sPC2) ((**a**) and (**b**), respectively) and social dimensions (sPC9 and sPC10) ((**c**) and (**d**), respectively). Categories correspond to distribution quartiles.

4. Discussion

The role of human dimensions in forestry practices, including socio-economic factors, cultural aspects, and the impact of community involvement in afforestation projects, is often neglected. In Chile, the existing industrial forest plantation model that seeks to maximize profit [22,40] is appropriate for large landowners and forestry companies that can take advantage of economies of scale, but it is not suitable for small and medium forest landowners [41–43]. This forestry model faces increasing social demands such as the reduction of income inequalities [44] and the inclusion of local and indigenous communities [45]. These gaps highlight the need for developing a new productive model to ensure a fair wealth distribution [46].

P. pinea plantations emerge as a suitable productive alternative for small and medium landowners, since unlike forestry plantations, they allow for annual cash income from pine nut production. This is key for small and medium landowners whose alternative is extensive livestock farming. Therefore, *P. pinea* plantations would recover the land's capacity to produce food and generate an annual income [15,47], favoring sustainable and inclusive rural development with economic, social, and environmental benefits. *P. pinea* afforestation is also important for environmental conservation, soil restoration, and recovery of the site's productive capacity [48]. Furthermore, this crop can be easily implemented by small and medium-sized landowners with limited capital and knowledge.

Strategic spatial planning of stone pine in Chile is crucial for sustainable development since the commercialization of pine nuts could contribute to the improvement of the rural economy, as has been reported in Turkey, Lebanon, Tunisia, and several European countries [49,50]. Using a spatial methodology, we observed that the spatial patterns of PPI for the species were strongly regulated by the spatial pattern of environmental variables such as PP, soil texture, and AWC. Similarly, MDI was strongly regulated by the spatial patterns of the three dimensions of human development, especially by education and economy. The spatial pattern of MDI was not associated with the greatest spatial variability and showed a negative spatial correlation. This result indicates an expelling mechanism whereby municipality development can negatively affect the MDI of neighboring municipalities, reflecting a concentration of development. In fact, Aroca et al. [51] reported an increasing spatial concentration resulting in negative effects on national growth in Chile. This spatial concentration is partially explained by industrial areas located near ports, characterized by service infrastructure and labor availability. Surprisingly, we found that the education dimension has a different spatial behavior than that of the welfare dimension.

The areas suitable for afforestation policies are those with high PPI, high clay content in non-clayey soil textural classes, located far from mountain ranges, in little-developed municipalities around larger cities, and with little welfare but with high values of education. This result is in agreement with reports from the species' native habitat, where a high soil clay content was found to be a limiting factor for *P. pinea* productivity [52,53]. However, the soils included in this study contain clay levels below 40%, i.e., that are non-clayey soils. In these non-clayey soils, a high clay content supports successful *P. pinea* plantations probably because they have high water holding capacity and fertility, two factors that are positively correlated with PPI.

If we consider von Thunen's logic, the farther the area is from the markets, the lower the profitability due to transportation costs. That said, areas with high PPI surrounding urban centers, industrial areas, and ports present comparative advantages. Now, if these rural areas surrounding said urban centers are economically depressed, as reflected in the low income of rural families and the marginal agricultural lands where they live, the production of a forest species with high-value nuts provides an opportunity to generate annual cash income and new rural jobs, as also reported for other countries [14]. Thus, there are important areas where the cultivation of the species would have a positive economic and social impact, increasing variables that define human development. These positive effects would directly benefit the population of numerous municipalities, including several poor and unequal ones, a central issue for research and policy agendas [44].

According to Quevedo [54], development should be measured not only in income terms, but also considering the varied realities across the territory, including the economic, human, institutional, and cultural aspects involved in the potential for human development. An inclusive planning approach prioritizing low MDI municipalities would set the path towards sustainable development [17] in which both women and men can participate [18], contributing to gender equality. In Turkey, in the Kozak basin, the development of the *P. pinea* productive chain improved the economic situation and progressively increased job opportunities as the cultivation of the species advanced. These positive effects were reflected in greater purchasing power, the possibility of traveling for vacation, greater cultural activity, and reinforced social cohesion. In addition, cooperatives were created to process and sell pine nuts [55], contributing to a better public relationship with the forests [56]. Moreover, in Anatolia, another region of Turkey, [57] observed positive environmental (improved soil quality) and socio-economic effects of *P. pinea* afforestation, with an increase in the population income from the commercialization of wood and pine nuts. In Tunisia, the establishment of local micro-enterprises specializing in pine nut extraction allowed the development of a business-integrated model [18].

By considering the potential socio-economic and environmental benefits of *P. pinea* cropping, policymakers might make informed decisions about where to focus afforestation efforts, reducing uncertainty and risks [58], especially related to climate change. Climate resiliency at the farm level is essential to achieve food security and improve the livelihoods of rural communities [5]. Therefore, the high adaptability of *P. pinea* to a wide range of climatic conditions would allow policymakers to anticipate changes and identify opportunities for adaptation; for example, farmers can be encouraged to establish *P. pinea* plantations in zones identified as feasible and strategic. The importance of the anticipation of external changes for the appropriate design of public policies related to land allocation and land-use changes in Chile has been studied by [59]. Since productive and social dimensions are difficult to integrate (productive dimensions present a geographical gradient while social dimensions are cryptic), planning *P. pinea* plantations should involve two sequential stages to boost rural-promoting policies. First, it should be considered the species' productive potential and secondly, the municipality's development level.

One of the challenges faced during the study is that the integration of information layers at different scales limits the interpretation of the study results; this issue could be addressed in future research by using fine grids for variable characterization. Further studies in this field could also incorporate new variables to better establish priorities set objectives and devise strategies to deal with risks. Aggregates of land with homogeneous attributes smaller than a municipality can be identified, aiming to reflect microsite and microclimatic characteristics to target priority areas with productive potential in areas with great needs of human and economic development, including variables such as household income and rural employment generation, and access to basic services such as quality education and health.

In all *P. pinea* productive and non-productive areas, there are different social scenarios that should be considered when planning municipality development. The results are an important input for future policy design and implementation. From a methodological viewpoint, the approach provides new insights into the analysis of the complexity of multidimensionality by including social aspects in the promotion of *P. pinea* productive plantations. This is especially relevant in Chile, a country characterized by high levels of spatial concentration of population and production, and significant spatial inequalities [60], as well as latitudinal weather differences that affect productivity [61].

The application of our results might enhance the development of municipalities through the incorporation of small and medium landowners and SMEs into sustainable forest activity. In particular, the described spatial patterns could justify a government program of economic incentives to encourage small and medium farm households to crop the species in order to improve the rural economy in poorly developed municipalities, thus articulating private landowners' decisions to enhance social well-being. Providing such incentives would allow overcoming the barriers to developing *P. pinea* plantations in low MDI areas, facilitating the transition to a bioeconomy.

5. Conclusions

We found heterogeneity in the spatial pattern of productive and social variables related to stone pine spatial distribution. In particular, PPI presented a latitudinal and longitudinal gradient, while social variables appeared as a mosaic. The main determinants of the current spatial distribution of stone pine plantations in Chile have been social and cultural rather than ecological ones. The barriers for stone pine development in low MDI areas are mainly the lack of knowledge of this species' productive potential and the lack of financial resources to establish new plantations. Therefore, public education and economic incentives would be a helpful strategy to assist in new the plantations establishment in low MDI areas. Public policies aimed at boosting municipality development through the promotion of *P. pinea* plantations could target zones with, first, a high productive potential and, second, a low MDI to generate socio-economic improvement. These findings are useful for the strategic spatial planning of the species cropping in Chile.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15091537/s1, Table S1: MULTISPATI-PCA results. Table S2: Pearson correlation coefficients of each original variable with each synthetic variable.

Author Contributions: All authors contributed to the study conception and design. Data collection and preparation were performed by R.D.R. C.D. participated in the statistical analyses and bibliographical review. M.B. led the statistical analysis. R.G. contributed to the discussion section. V.L.-M. wrote the first draft of the manuscript and all authors commented on successive versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The datasets generated and analyzed during the current study are not publicly available due to institutional guidelines, but are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

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