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Increased Production of Tara (*Caesalpinia spinosa*) by Edaphoclimatic Variation in the Altitudinal Gradient of the Peruvian Andes

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Abstract: Tara production occurs mainly in the altitude gradient, where the edaphoclimatic conditions that affect the production of pods still need to be understood. The goal was to determine the altitudinal and edaphoclimatic effect on the production of tara pods in agroforestry and natural remnants in Cajamarca, Peru. Data analyses performed were the following: principal component analysis (PCA), regression analysis, the bootstrap method, and Pearson correlation analysis. For each 1 °C increase in temperature, the length and width of the pod decreased by 2.1 and 0.62 mm, and of the seed by 0.17 and 0.12 mm in the agroforestry environment; likewise, pod, valve, seed and gum weights were reduced by 23.9, 10.9, 13 and 2.3 g in the agroforestry environment, and 22.3, 13, 9.3 and 2.1 g in the natural environment. Activities such as association with annual crops and perennial pasture possibly favor the length and width of the pod and seed and the weight of the pod, valve, seed and gum in the agroforestry environment when compared to the natural environment. Larger pod and seed dimensions and higher pod, valve, seed and gum weights are related to higher soil $CaCO_3$ contents in the natural environment and higher soil P and B contents in the agroforestry environment at higher altitudes. Higher Fe contents in the soil suggest an improvement in tara's tannin weight (valve) in the natural and agroforestry environment. The effective response of tara, reflected in its weight and size of pods, was higher in an agroforestry environment than in a natural environment. Further studies on the production of tara pods are necessary for a better understanding of the interaction between altitude and soil fertility to expand the revenue and employment of Peruvian tara farmers.

Keywords: soil; temperature; altitude; tannin; gum

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1. Introduction

Caesalpinia spinosa is a plant species native to the Andes of Peru, known as tara [1], which produces pods of high economic value due to the presence of tannins in the valves and gum in the endosperm of the seeds. Tannins are extensively applied in the pharmaceutical, chemical, and furnishing industries, among others [2–6] and have astringent, anti-inflammatory, antiseptic, antitumor, antimicrobial and antioxidant properties [7–12]. In phytosanitary control, tannins are used due to their antifungal and antibacterial properties [9,11]. The gum is a polysaccharide composed of 78.0% galactomannans or soluble fiber [7] used in the cosmetic and nutrition industries; as a food additive, it is not hydrolyzed by gastrointestinal enzymes, that is, it is not digestible [13–16]. In environmental restoration, its use in water treatment as a bio coagulant and flocculant biopolymer stands out (S). The tara tannin and gum applied in the industry are environmentally sustainable as they do not generate toxic waste [17].

Peru is responsible for 85% of the world's production of all tannins and gum; in 2018, it exported 31,442 t in the form of tannin (powdered valves) and gum (seed endosperm), with the North, Cajamarca and La Libertad regions representing 50% of national production [18]. Tara derivatives have a global demand of 42,326 t yr^{-1}, equivalent to a pod production of 80,000 t yr^{-1} [6]; the supply of tannin and gum in the international market is deficient. The production of tara pods comes from small areas of natural remnants or from agroforestry systems of family agriculture, dispersed in an altitudinal gradient of the Andes, where the edaphoclimatic conditions vary in space and time. In the Peruvian tropical Andes, with anthropic management or in natural systems, soils vary depending on topography [19]. Despite the fact that soil fertilization takes place in agroforestry systems, there is great similarity in the attributes of these soils in relation to those of natural forests [19,20]. Agroforestry systems favor agrobiodiversity, diversified livelihoods, food security and sovereignty, improved economic income, and reduced impacts on climate change [21–23]. Natural systems, in turn, maintain ecosystem services, such as soil and water preservation [24–26].

Air temperature decreases with increasing altitude [27–29]. Under these conditions, the stages of plant development are delayed [27]. Melo et al. [30] detected that the reproductive phase of tara at 3000 m altitude occurred in 195 days, whereas Murga-Orrillo et al. [31] found that at 2260 m altitude, this period was 180 days. Among these surveys, there is a spatial difference of 740 m in altitude and a temporal difference of 15 days in the reproductive period of tara. It is crucial to determine whether tannins and tara gum production vary in the altitude gradient as a function of the production system or due to soil fertility variables, as this will improve production and marketing management.

Understanding the edaphoclimatic variations in altitudinal gradient makes it possible to determine which environmental factors favor the production of tannins and gum in tara pods, relevant information to enhance production systems and reforestation practices in potentially useful areas for competitive and sustainable production. In this sense, we proposed to determine the altitudinal and edaphoclimatic influence on the production of tara pods in agroforestry and natural remnants in Cajamarca, Peru.

2. Material and Methods

2.1. Characterization of the Study Area

The study area location, altitudinal gradient, climate and geographic coordinates are described in Table 1, and correspond to previous work executed by Murga-Orrillo et al. [32].

Table 1. Weather stations, with latitude (ϕ, °S), longitude (λ, °W) and altitude (z, masl).

Station	ϕ	λ	z	Station	ϕ	λ	z
San Marcos	7.32	78.17	2293	Gregorio Pita	7.23	78.21	2908
Cajabamba	7.62	78.05	2626	La Fortuna	7.67	78.40	3326
Cachachi	7.45	78.27	3228	Lucma	7.64	78.55	2225
Cospan	7.42	78.54	2423	Magdalena	7.25	78.65	1307
Encañada	7.12	78.33	2980	Quiruvilca	8.00	78.30	4047

2.2. Delimitation of Instalments

Thirty-one plots were installed in the province of San Marcos, a region of Cajamarca. The plots were grouped into two environments: an environment with remaining natural forests, with 15 plots between altitudes from 2021 to 2953 m, and an environment in agroforestry systems with trees originating from tara associated with *Medicago sativa*, *Lolium multiflorum*, *Zea mays*, *Phaseolus vulgaris*, *Triticum aestivum*, *Linum usitatissimum* and *Vicia faba* (Table 2) covering 16 experimental plots between altitudes from 2152 to 3101 m.

Table 2. Number of seeds per pod (NS), pod width (PW), pod length (PL), seed length (SL) and seed width (SW) of tara in natural and agroforestry environments in Cajamarca, Peru.

Altitude *	NS	PL	PW	SL	SW
m		cm			
Natural environment					
2021	5.18 ± 1.21	9.34 ± 0.93	2.05 ± 0.16	0.58 ± 0.05	0.47 ± 0.05
2185 ± 37	4.23 ± 1.57	8.69 ± 0.93	2.22 ± 0.19	0.67 ± 0.09	0.46 ± 0.07
2388 ± 51	4.75 ± 1.36	8.54 ± 0.92	2.17 ± 0.21	0.64 ± 0.07	0.47 ± 0.08
2546 ± 62	4.36 ± 1.47	8.54 ± 1.30	2.04 ± 0.16	0.63 ± 0.08	0.45 ± 0.07
2680 ± 76	4.11 ± 1.54	9.01 ± 1.07	2.26 ± 0.21	0.69 ± 0.09	0.45 ± 0.07
2798 ± 21	5.80 ± 1.41	9.98 ± 1.31	2.42 ± 0.17	0.64 ± 0.06	0.48 ± 0.05
3007	3.88 ± 1.15	7.93 ± 0.87	2.14 ± 0.14	0.75 ± 0.08	0.51 ± 0.07
Mean	4.62 ± 0.68	8.86 ± 0.66	2.19 ± 0.13	0.66 ± 0.05	0.47 ± 0.02
Agroforestry environment					
2185 ± 35	4.43 ± 1.64	8.88 ± 1.02	2.15 ± 0.16	0.66 ± 0.07	0.43 ± 0.06
M. sativa, *L. multiflorum*					
2388 ± 26	4.80 ± 1.47	9.12 ± 0.96	2.30 ± 0.16	0.66 ± 0.08	0.48 ± 0.07
Z. mays, *P. vulgaris*, *T. aestivum*					
2546	3.88 ± 1.81	8.91 ± 1.28	2.14 ± 0.19	0.70 ± 0.10	0.48 ± 0.09
Z. mays, *P. vulgaris*					
2680 ± 64	3.62 ± 1.18	9.36 ± 1.51	2.38 ± 0.25	0.68 ± 0.07	0.48 ± 0.05
Z. mays, *P. vulgaris*, *M. sativa*, *L. multiflorum*					
2680 ± 64	5.06 ± 1.32	9.46 ± 0.98	2.53 ± 0.21	0.68 ± 0.08	0.49 ± 0.05
Z. mays, *P. vulgaris*					
3007 ± 76	5.26 ± 1.42	9.55 ± 1.17	2.41 ± 0.19	0.74 ± 0.06	0.50 ± 0.06
Z. mays, *V. faba*, *L. usitatissimum*					
Mean	4.51 ± 0.65	9.21 ± 0.29	2.32 ± 0.15	0.69 ± 0.03	0.48 ± 0.02

*—standard deviation (±).

The plots, with an area of 200 m^2 were georeferenced according to Murga-Orrillo et al. [32].

2.3. Soil Sampling and Analysis

In each plot, five 1 kg soil subsamples were collected at a depth of 0 to 40 cm, which were later mixed, forming a composite sample. Each subsample weighed 1 kg, forming a total mixture of 5 kg, which was homogenized in a single sample of 1 kg of soil per plot, following the methodology of Embrapa [33].

Prior to analysis, the samples were dried and then refrigerated following the methodology described in Murga-Orrillo et al. [32]. Analyses were executed in the Soil, Plant, Water and Fertilizer Analysis Laboratory of the La Molina National Agrarian University. We measure the following soil attributes: pH, electrical conductivity (EC), texture, nitrogen (N), phosphorus (P), magnesium (Mg), zinc (Zn), calcium (Ca), iron (Fe), sodium (Na), manganese (Mn), boron (B), potassium (K), copper (Cu), limestone ($CaCO_3$), organic matter (OM) and cation exchange capacity (CEC). All analyses were completed according to standard methodology described in Murga-Orrillo et al. [32]. Embrapa classification was used in the soil's chemical properties [33].

2.4. Air Temperature Data

The average daily air temperature data from October 2019 to July 2020 from ten weather stations near the study area (Table 1) were made accessible by SENAMHI, which were used to create a multiple linear regression model of the average daily temperature (Equation (1)), as a function of altitude (z) and astronomical length of the day (Ω). Significant parameters were obtained from $p < 0.001$ for z and Ω, from $p < 0.01$ for $z^*\Omega$, with R2 $Aj = 0.86$. With this model, the daily temperatures of the tara reproductive period were estimated; through these data, the monthly mean temperature of the period (MTP) of evaluation of the tara reproductive phase was then determined.

Equation (2) was applied to calculate the Ω while determining the hourly angle of sunrise or sunset (H) and the declination angle of the sun (δ) for the meteorological stations (Equations (3) and (4)).

$$DAT = 14.9274 - 0.001396965z + 1.288206\Omega - 0.0003408548z\Omega \quad (1)$$

$$\Omega = 2(H + 0.83)/15 \quad (2)$$

$$H = arccos(-tan\phi tan\delta) \quad (3)$$

$$\delta = 23.45sen[2\pi/365(284 + jd)] \quad (4)$$

where DAT = daily average temperature (°C), z = altitude (masl), Ω = astronomical length of day (h/day), H = hourly angle of sunrise or sunset (degrees), ϕ = latitude (degrees), δ = sun declination angle (degrees), jd = Julian days.

2.5. Physical Characterization of Pods and Seeds

The commercial maturation of pods (pods with valves and dry seeds) is asynchronous in trees and varies at different altitudes (Figure 1a), starting the collection of pods on 02/29/2020 at 2021 m altitude and concluding on 07/15/2020 at 3101 m altitude. In these plots, 2 kg of tara pods (total 62 kg) were collected in zip lock bags from the middle third of the tree canopies. After collecting the last sample, all samples were stored in a single ventilated environment, under the shade, for 60 days. Then, the physical characterization of 50 pods and 50 seeds per sample was carried out in a total of 800 pods and seeds for the agroforestry environment (16 plots) and 750 pods and seeds for the natural environment (15 plots). These evaluations were performed with a tape measure (Figure 1b) and a caliper (LEETOOLS-684132), to measure the length and width of the pods and seeds. As for weighing, 100 pods per plot were considered, totaling 1600 pods for the agroforestry environment and 1500 pods for the natural environment, and the valves and seeds were manually separated. From the seeds obtained from the 100 pods/plot, the gum (endosperm of the seeds) was extracted. Due to the hardness of the seed coat, they were manually scarified with No 20 sandpaper and then hydrated in 0.5 L of water/sample/2 days. After hydration, it was easy to separate the gum from the tegument and cotyledons with the aid of a scalpel (Figure 1c). The gum was dried in a ventilated and shaded environment to carry out weightings until the samples had a constant weight, which occurred after ten days. The weighing of pods, valves, seeds and starch was performed with a scale model BM-SM1 (Shanghai, China).

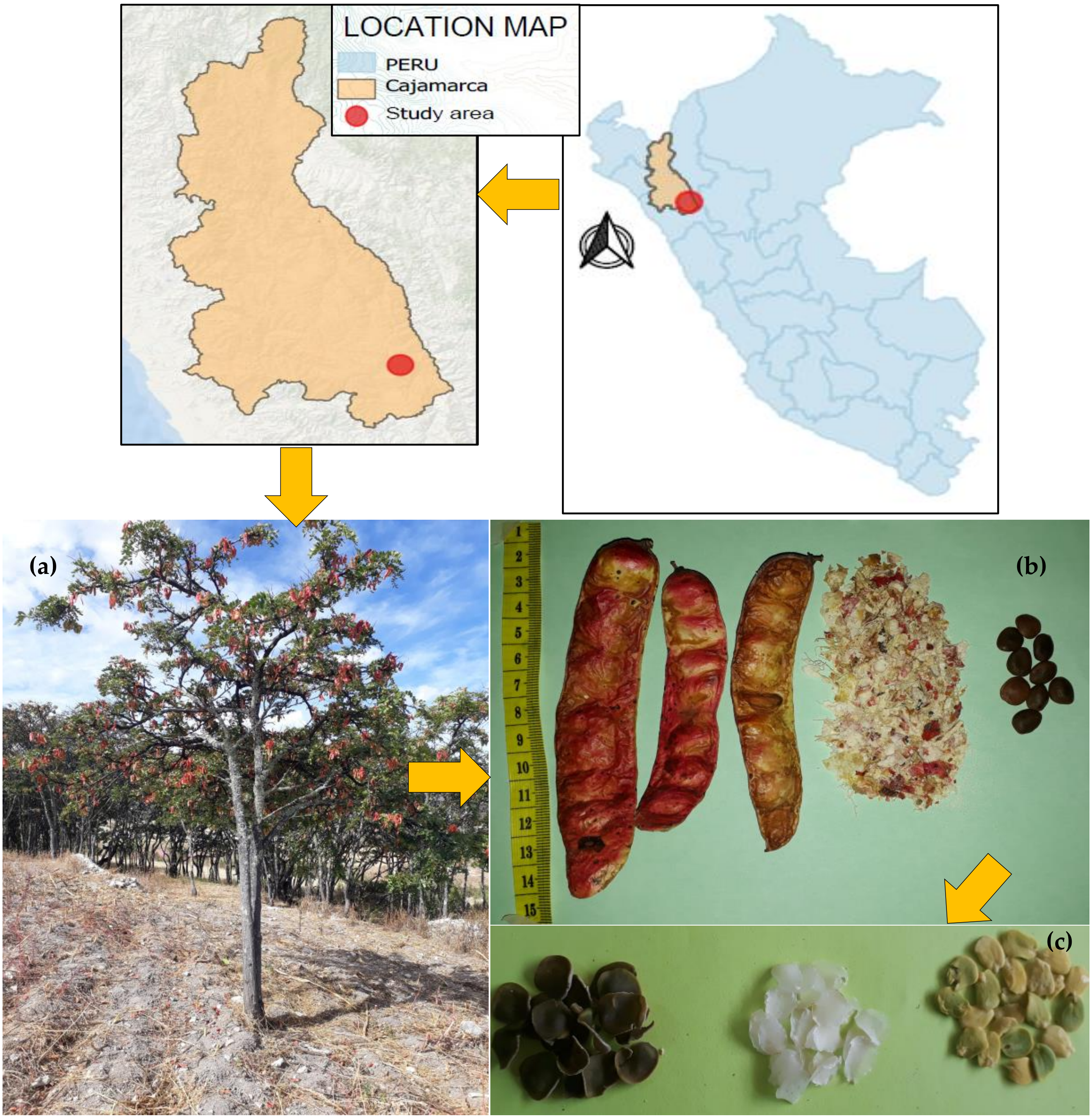

Figure 1. Tara tree with pods at commercial maturity (**a**), tara pods with the extraction of valves (tannin) and seed (**b**), seed coat, gum and cotyledons (**c**), in Cajamarca, Peru.

2.6. Grouping of Variables

For data analysis, two environments were grouped: (1) agroforestry (16 plots) and (2) natural (15 plots). Seven classes of altitudes were determined (2021, 2185, 2388, 2546, 2680, 2798 and 3007 m), consequently corresponding to seven classes of temperatures (19.8, 18.5, 17.3, 16.4, 15.6, 14.6 and 13.4 °C) per degree (−1 °C) of variation in the annual mean temperature due to the increase in altitude. In these classes, the monthly temperature of the evaluation period of the tara reproductive phase was grouped (Figure S1).

2.7. Statistical Analysis

The characterization of the average daily temperature was performed using multiple linear regression, with quantitative analysis of data normality, outliers in the residuals, independence of the residuals, homoscedasticity of variances, multicollinearity and ANOVA of the model, based on information on daily temperatures of the 10 months that the reproductive period of the tara lasted, and from 10 climatological stations with records of longitude, altitude and estimate of the astronomical duration of the day, as described in the item "Air temperature data". The MTP data obtained from the daily average temperature were compared with the historical monthly average temperature of 25 years, using the Student's *t*-test ($p < 0.05$).

In order to evaluate possible discriminations between the evaluated factors, namely, the production systems and the altitude classes, PCA analyses were carried out in different ways. They started with global cluster analyses to assess possible differences between production systems (independently of altitudinal classes) or between altitudinal classes (independently of production systems). Then, PCAs were generated for each production system to evaluate possible discriminations between the altitudinal classes within each system and for each altitudinal class to assess possible discriminations between production systems within each class. In all cases, the most correlated variables were selected according to the methodology of Jolliffe [34]. Then, the mean values and respective non-parametric confidence intervals were obtained by the bootstrap technique, with 100,000 resamplings with replacement of these variables, to identify which of them could be the one that most influenced the discrimination of production ´systems or classes' altitudinal values in PCA analyses. For each production system, the effects of altitude and temperature on the weight of pods, seeds, valves and gum were evaluated using linear regression analysis. Finally, for each production system, Pearson correlation analyses were performed between dimensions, valve weights and soil attributes. All analyses were performed using FactoMineR, factoextra, corrplot, ggplot2, tidyverse and boot packages [35].

3. Results

3.1. The Average Temperature of the Tara Reproductive Period

The decrease in temperature with increasing altitude shows significant differences (Figure S1). Consequently, this variation tends to influence the duration of tara pods' reproductive phase and commercial maturation. Between the minimum and maximum altitudes of the study area, there was a variation of two months for the beginning of the flowering phase of tara, starting in November 2019 at altitude 2021 m and in January 2020 at altitude 3101 m; the commercial maturation of pods showed a variation of five months, with pod harvests occurring in March 2020 at an altitude of 2021 m and in July 2020 at an altitude of 3101 m. At these altitudes, the average monthly temperature also varied by 6 °C; at altitude 2021 m, the temperature was 19.4 °C (Class 2021 m), and at altitude 3101 m, it was 13.4 °C (Class 3007 m), respectively. The beginning of the activation of the reproductive phase of tara depends on the rainy season, which starts between October and December.

3.2. Dimensions of Pods and Seeds

Table 2 shows the number of seeds per pod, pod length, pod width, seed length and seed width for the natural and agroforestry environment. The altitudinal classes between 2021 and 3007 m (Figure 2a,b) and between 2185 and 3007 m (Figure 2c) show differences in seed length and width, with higher values for the 3007 m class. In the soil of the natural and agroforestry environments, at 3007 m, there are higher levels of $CaCO_3$ than at 2021 m (Figure S5); individually, the soil of the natural environment, at 3007 m, has higher levels of $CaCO_3$, CEC, Mn and Fe than at 2021 m (Figure S5); and in agroforestry soils, at 3007 m there are higher levels of P, K and B than at 2185 m (Figure S2).

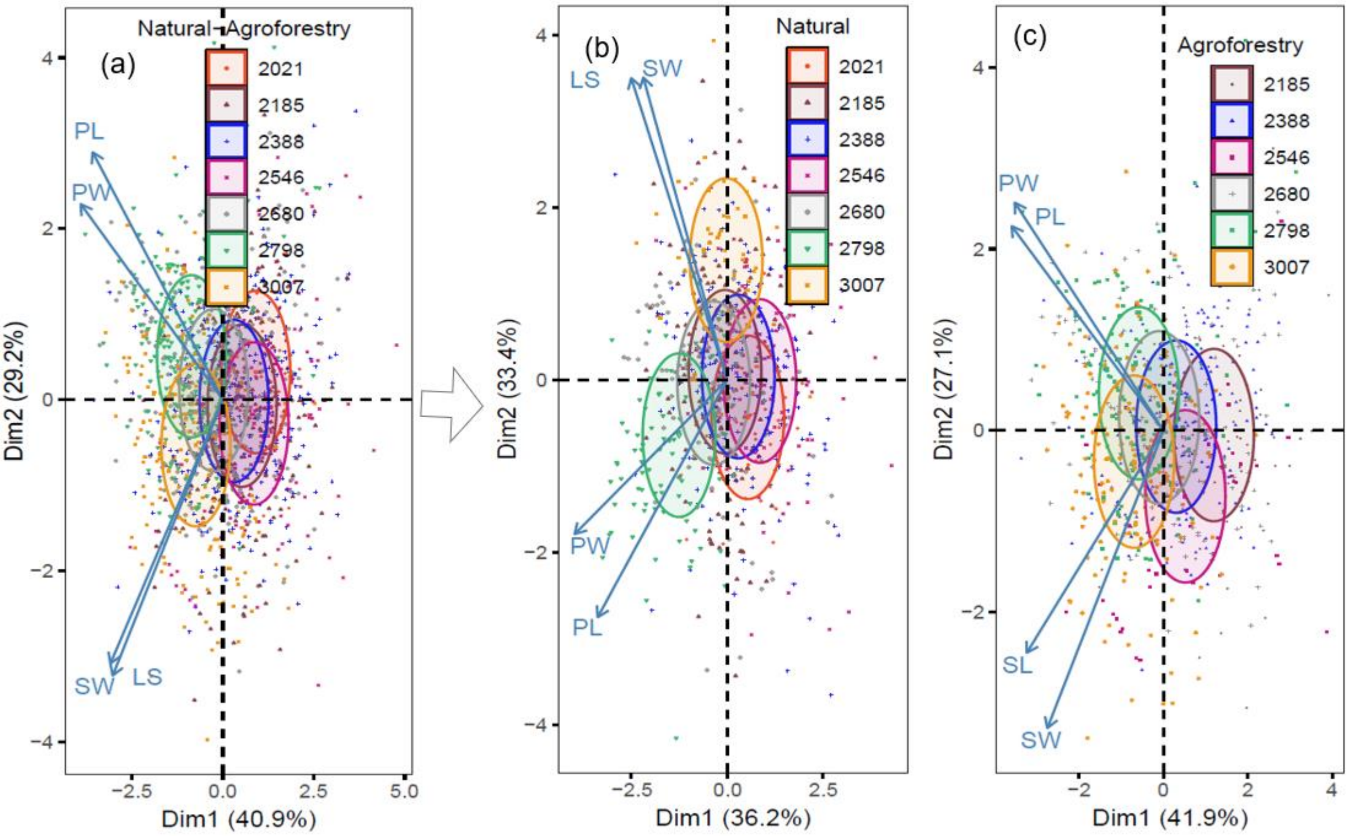

Figure 2. Principal component analysis (PCA) of pod width (PW), pod length (PL), seed length (SL), and seed width (SW) of tara. (**a**) all altitude classes within the natural and agroforestry environments, (**b**) altitude classes for the natural environment, and (**c**) altitude classes for the agroforestry environment.

In the PCAs related to the tara production variables, differences are observed between the 2546 and 2798 m altitude classes for the grouped production systems (Figure 2a) and individually natural (Figure 2b) and agroforestry (Figure 2c), with higher values of pod width and length for the 2798 m class. As for soil attributes at these altitudes, Fe content was lower at 2798 m than at 2546 m for the grouped environments (Figure S4) and equal in the natural (Figure S5) and agroforestry (Figure S2) environments individually. In the natural environment, Cu was higher at 2798 m than at 2546 m (Figure S5), whereas in the agroforestry environment, P, B and $CaCO_3$ were higher at 2798 m than at 2546 m (Figure S2).

The correlations of pod and seed dimensions with soil attributes (Figure 7) in the agroforestry environment (Figure 7b) show positive correlations of B with pod length ($r = 0.67$, $p < 0.01$), with the seed length ($r = 0.58$, $p < 0.05$) and seed width ($r = 0.59$, $p < 0.05$), and of the P with the seed length ($r = 0.55$, $p < 0.05$).

In the PCAs of Figure 3, in general, pod width and length and seed width and length do not vary between natural and agroforestry environments grouped (Figure 3a). Similar results occurs in the comparison between the natural and agroforestry environment in the individual classes at 2185 m (Figure 3b), 2388 m (Figure 3c), 2546 m (Figure 3d), 2680 m (Figure 3e) and 2798 m (Figure 3f), but difference between these production systems only exists at the 3007 m class (Figure 3g), with higher values of pod width and length for the agroforestry environment when compared to the natural environment. At other altitudes, there are no differences between the production systems, showing that human activities do not influence the size of pods and seeds of tara in the agroforestry environment at lower altitudes. At 3007 m altitude, soil K, P, B and $CaCO_3$ were higher in agroforestry than in natural environments (Figure S3).

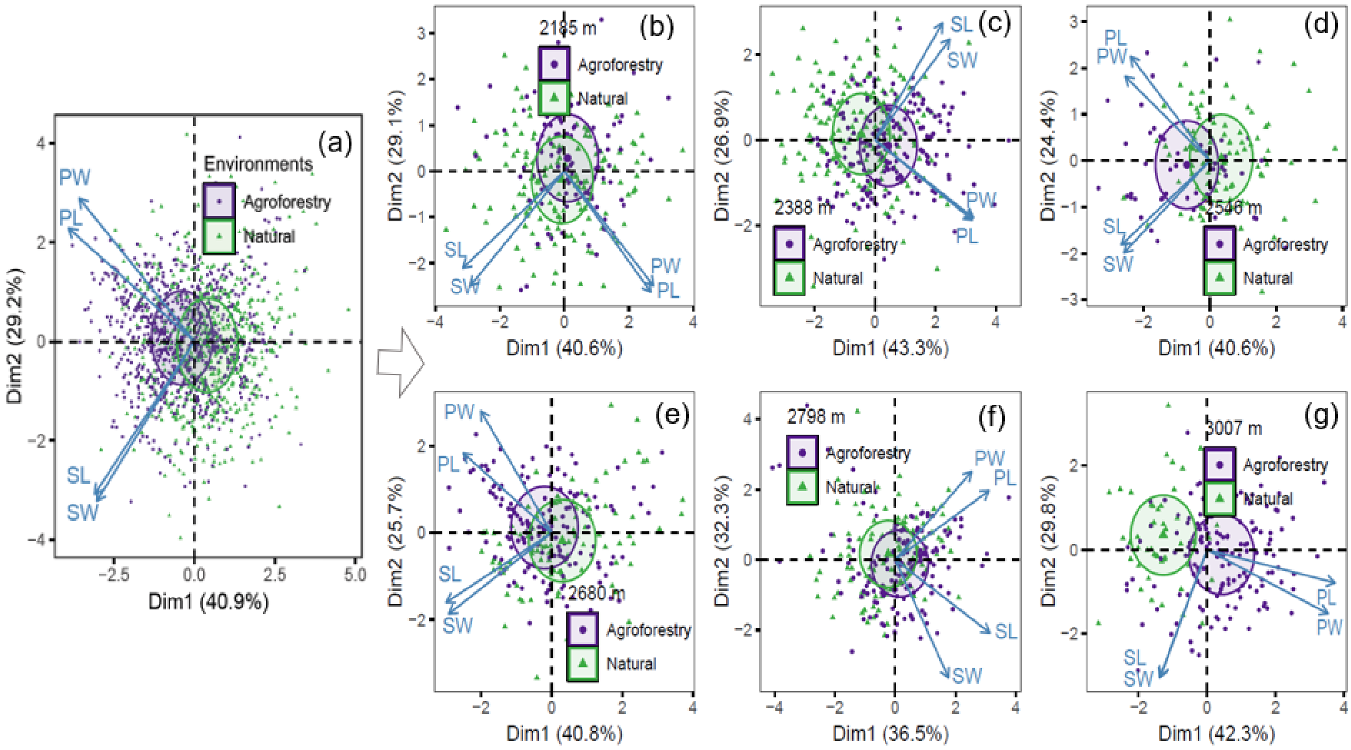

Figure 3. Principal component analysis (PCA) of pod width (PW), pod length (PL), seed length (SL), and seed width (SW) of tara. All plots (**a**), plots at altitude 2185 m (**b**), altitude 2388 m (**c**), altitude 2546 m (**d**), altitude 2680 m (**e**), altitude 2798 m (**f**), and altitude 3007 m (**g**), in natural and agroforestry environments.

Length and width of the pod and seed in the natural environment did not adjust to the linear regression model (Figure 4a–h). However, when it came to the agroforestry environment, the length and width of the pod and seed did fit to the linear regression models (Figure 4a–h), which allow estimating increments in pod length and width of 1.16 (1.4%) and 0.34 (1.6%) mm, of the length and width of the seed in 0.09 (1.5%) and 0.06 (1.4%) mm for the increase of 100 m of altitude; in contrast, it decreases the length and width of the pod by 2.1 (2.2%) and 0.62 (2.5%) mm, and the length and width of the seed by 0.17 (2.3%) and 0.12 (2.3%) mm by increasing the temperature by 1 °C.

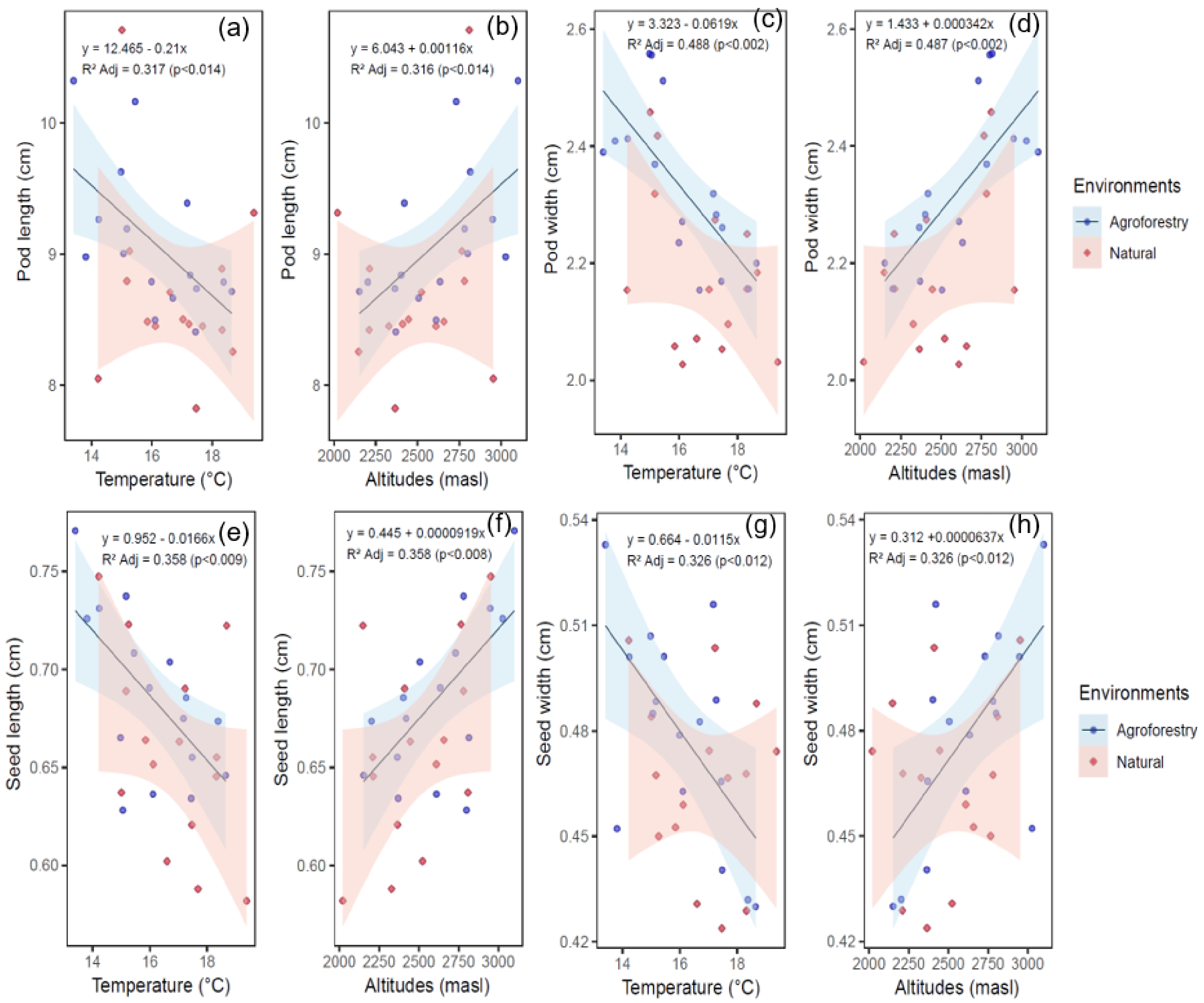

Figure 4. Influence of altitude and temperature on pod length and width dimensions (**a**–**d**), seed length and width (**e**–**h**) of tara in natural and agroforestry environments.

3.3. Weight of Tara Pods, Valves, Seeds and Gum

For the natural environment, the average weight of 100 pods was 264 g; of this value, 67% were valves, and 33% were seeds; concerning gum, it represented 5.6% of the pod weight and 16.9% of the seed weight; similarly, in the agroforestry environment, the average weight of 100 pods was 274 g, of which 67.9% were valves, and 32.1% was from seeds; the gum represented 6.1% of the pod weight and 18.1% of the seed weight (Table 3). Also, all these weights were higher in the agroforestry environment compared to the natural environment (Table 3).

Table 3. Sample of 100 pods in natural and agroforestry environments, pod weight, valve weight, seed weight, and gum weight of tara, for each altitude.

Altitude *	Pod	Valve	Seed	Gum
m		g		
		Natural environment		
2021	214	140	74	13
2185 ± 37	236 ± 10	167 ± 17	69 ± 12	11 ± 1
2388 ± 51	234 ± 23	155 ± 16	80 ± 10	13 ± 3
2546 ± 62	242 ± 17	164 ± 8	78 ± 8	12 ± 4
2680 ± 76	271 ± 37	186 ± 25	85 ± 13	14 ± 2
2798 ± 21	324 ± 52	202 ± 33	122 ± 20	23 ± 3
3007	325	222	103	20
Mean	264 ± 45	176 ± 28	87 ± 19	15 ± 5
		Agroforestry environment		
2185 ± 35	234 ± 2	166 ± 1	68 ± 1	13 ± 0
		M. sativa, *L. multiflorum*		
2388 ± 26	273 ± 9	186 ± 9	87 ± 7	16 ± 1
		Z. mays, *P. vulgaris*, *T. aestivum*		
2546	252	177	75	14
		Z. mays, *P. vulgaris*		
2680 ± 64	299 ± 63	230 ± 57	69 ± 7	13 ± 1
		Z. mays, *P. vulgaris*, *M. sativa*, *L. multiflorum*		
2680 ± 64	339 ± 19	217 ± 15	122 ± 5	22 ± 1
		Z. mays, *P. vulgaris*		
3007 ± 76	332 ± 46	204 ± 29	128 ± 17	23 ± 3
		Z. mays, *V. faba*, *L. usitatissimum*		
Mean	274 ± 42	185 ± 27	89 ± 21	16 ± 4

*—standard deviation (±).

Regarding the weight of pods, valves, seeds and gum, when the PCAs (Dim 1) were performed on altitude classes with the natural and agroforestry environments grouped (Figure 5a) or individually to altitude classes for the natural environment (Figure 5b) or agroforestry environment (Figure 5c), differences can be observed in classes 2021, 2185, 2388, 2546 and 2680 m, concerning classes 2798 and 3007 m, since the latter have the highest weights of pods, valves, seeds and gum. The soil of the agroforestry and natural environment grouped, 2798 and 3007 m, have higher levels of $CaCO_3$ than at 2021 m (Figure S4). Individually in the natural environment's soil, 2798 and 3007 m have higher levels of $CaCO_3$ and CEC than at 2021, 2185, 2546 and 2680 m (Figure S5). Also, in the soil of the agroforestry environment, 2798 and 3007 m have higher levels of B, P and $CaCO_3$ than at 2546 m (Figure S2).

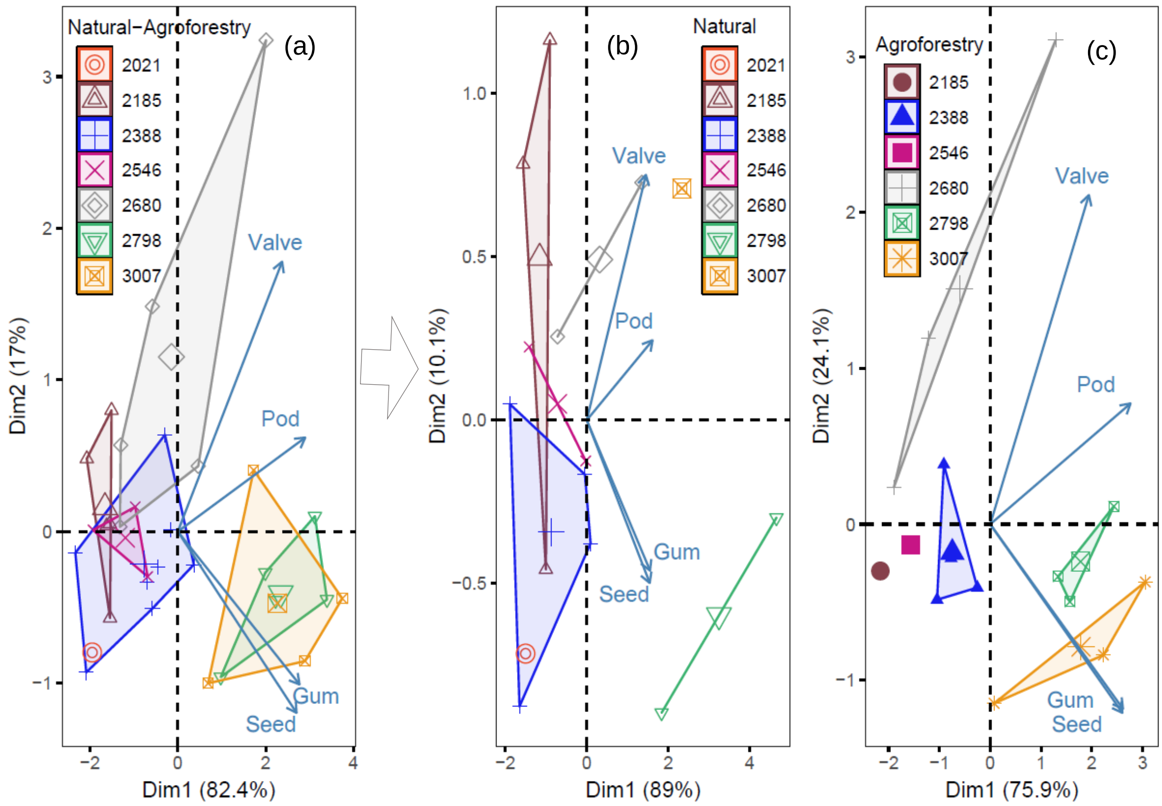

Figure 5. Principal component analysis (PCA) of the pod's weight (in g), pod valves, pod seeds and seed gum for 100 pods per plot of tara. (**a**) All environments within the different altitude classes, (**b**) altitude classes for the natural environment, and (**c**) altitude classes for the agroforestry environment.

In the PCAs (Dim 2) of the weight of the natural and agroforestry environment grouped, altitude class 2680 m has higher pod and valve weights, and 2798 m has higher seed and gum weights (Figure 5a); in the soil of these environments, 2680 m has higher Fe contents (Figure S4). Notably, in the natural environment, 2798 m has higher gum and seed weights, and 3007 m has higher pod and valve weights (Figure 5b); in the soil of this environment, 2798 m has the highest levels of $CaCO_3$ and B, and 3007 m has the highest CEC and Fe (Figure S5). In the agroforestry environment, 2680 m has higher pod and valve weights, meanwhile at 2798 and 3007 m have higher seed and gum weights (Figure 5c); in the soil of this environment, 2680 m has higher Fe contents, and 2798 and 3007 m have higher $CaCO_3$ contents (Figure S2).

Soil attributes present positive correlations with pod, valve, seed and gum weight (Figure 7). In the natural environment, Cu is correlated with gum weight (r = 0.52, $p < 0.05$) (Figure 7a); in the agroforestry environment, P is correlated with the weight of the pod (r = 0.56, $p < 0.05$), the seed (r = 0.70, $p < 0.01$) and the gum (r = 0, 71, $p < 0.01$), Fe with valve weight (r = 0.50, $p < 0.05$) and Mn with pod weight (r = 0.50, $p < 0.05$) (Figure 7b).

It was found that the weights of pods, valves, seeds and gum increased with altitude, which means that they changed with the reduction in mean air temperature (Figure 6). For each 100 m increase in altitude, the weights of pods, valves, seeds and gum increased by 13.7, 6, 7.2 and 1.3 g in the agroforestry environment and 12.3, 7.2, 5.1 and 1.1 g in the natural environment, respectively (Figure 6b,d,f,h). Thus, for each 1 °C increase in the average air temperature during the study period, the weights of pods, valves, seeds and gum were reduced by 23.9, 10.9, 13 and 2.3 g in the agroforestry environment, and 22.3, 13, 9.3 and 2.1 g in the natural environment, respectively (Figure 6a,c,e,g).

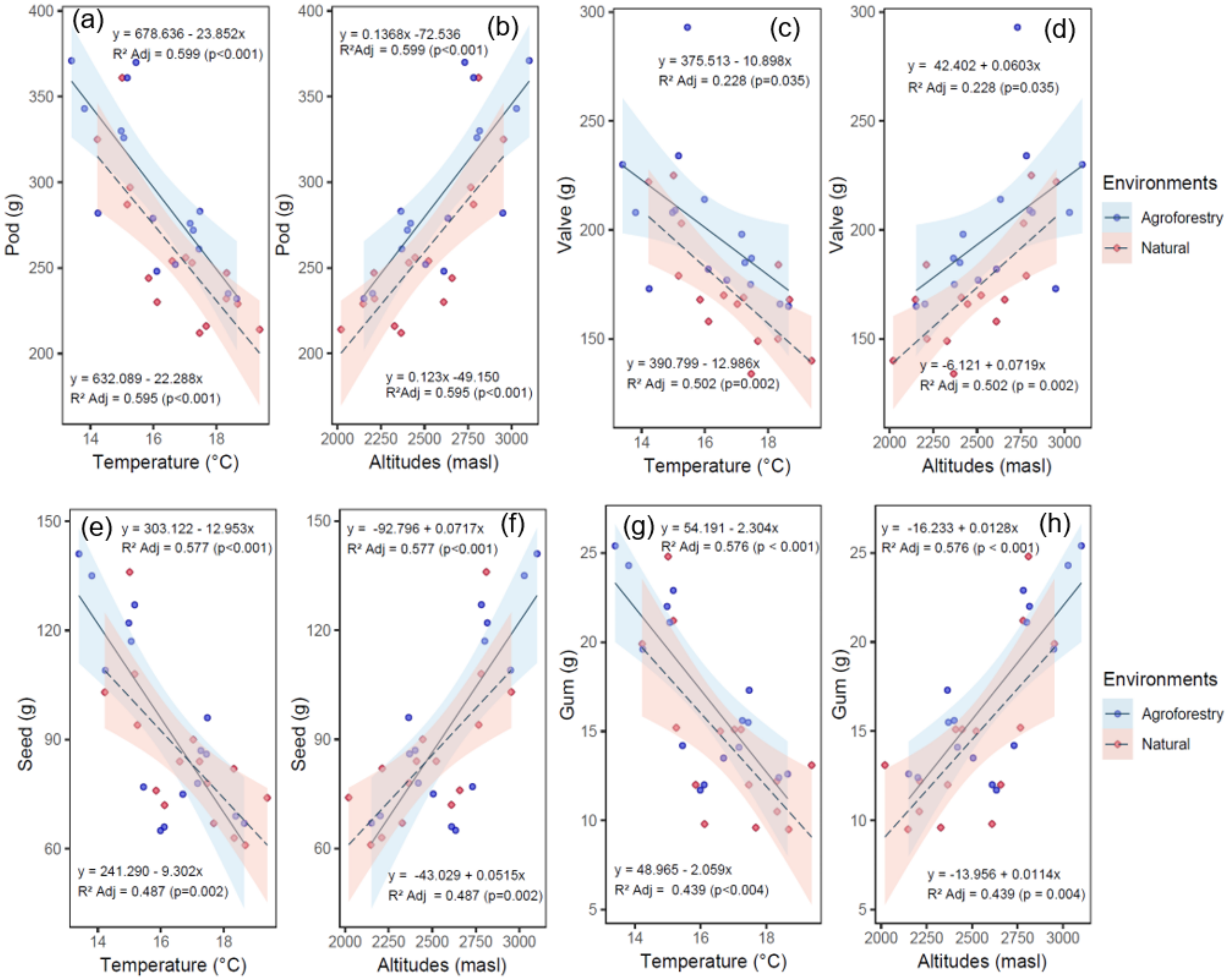

Figure 6. Weight regression analysis of a sample of 100 pods in natural and agroforestry environments. (**a**,**b**) pod weight, (**c**,**d**) valve weight, (**e**,**f**) seed weight, and (**g**,**h**) gum weight of tara, for temperature and altitude, respectively.

4. Discussion

4.1. The Average Temperature of the Tara Reproductive Period

The decrease in temperature with increasing altitude increases the reproductive time of tara by two months, being five months at altitude 2021 m and seven months at altitude 3101 m, since the variation of the average monthly temperature between these altitudes was 6 °C. Also, in the vegetative period of *Sabina przewalskii*, the annual growth was delayed by 3 to 4 days per 100 m increase in altitude, or increased by seven days per 1 °C increase in temperature [27]. Similarly, in *Camellia sinensis*, there was a longer duration of the shoot growth cycle due to the increase in altitude due to temperature differences [36].

4.2. Tara Pod and Seed Dimensions and Weight

The study area soils are limestone (Figures S2h, S4c and S5h). This condition possibly favors the production of tara pods. Limestone soils have $CaCO_3$ contents greater than 15% [37].

In the classes at 2798 and 3007 m, soil $CaCO_3$ shows significant differences (Figure S5) that produce the differences in PCAs for the natural environment, with greater pod lengths and width at 3007 m than at 2021 m (Figure 2b), and higher pod, valve, seed and gum weights at 2798 and 3007 m concerning the other altitudes (Figure 5b). Likewise, in the

PCA that compares the agroforestry and natural environments, at 3007 m, the agroforestry environment presents greater pod length and width (Figure 3g) associated with higher levels of P, K, B and $CaCO_3$ (Figure S3). In other Fabaceae, increasing $CaCO_3$ in the soil improved yield: 20-fold in *Coronilla varia*; 9 times in *Trifolium repens*; 6 times in *Leucaena leucocephala*, *Dolichos axillaris* and *Medicago sativa*; 5 times in *Glycine wightii*; 4 times in *P. vulgaris*; 3 times in *Lotus corniculatus*; and twice in *Desmodium canum*, *D. intortum* and *Trifolium subterraneum* [38].

In the agroforestry environment, regarding differences in PCAs, the largest dimensions of the seeds are associated with 3007 m compared with 2185 m (Figure 2c); the highest pod, valve, seed and gum weights are possibly associated with 2798 and 3007 m compared with the other altitudes (Figure 5c). These variations are probably due to significant differences in soil with higher levels of P, B and $CaCO_3$ in classes 2798 and 3007 m (Figure S2). Increasing soil $CaCO_3$ was found to directly affect soil P uptake in *Medicago* spp. and *Trifolium subterraneum* [39]. In *P. vulgaris*, applications of $CaCO_3$ doses led to an increase of 70 to 80 mg dm^{-3} of P in the soil, increasing P concentrations in the seeds, with yields of 3500 to 4100 kg ha^{-1}, respectively [40]. Also, concerning *P. vulgaris*, with the application of levels of 0, 10, 20 and 30 kg ha^{-1} of P and 0, 0.9, 1.8 and 2.7 t ha^{-1} of $CaCO_3$, higher grain yields were obtained at higher levels of P and $CaCO_3$ [41]. Now in *Vigna radiata* the combined effect of $CaCO_3$ with B in the soil had a significant effect on seed yield, in addition to having a strong correlation of total seed weight with total leaf B content [42].

The PCAs refer to weight (Figure 5) in the natural and agroforestry environment grouped at 2680 m (Figure 5a); individually, in the agroforestry environment at 2680 m (Figure 5c), and in the natural environment at 3007 m (Figure 5b), they are associated with higher tara valve weights. The soils of these altitudes' present contents of 47.6 ± 58.0, 65.5 ± 74.2 and 125.3 mg dm^{-3} of Fe for the natural and agroforestry environments grouped (Figure S4) and individually, agroforestry (Figure S2) and natural (Figure S5), respectively. In addition, Fe positively correlates with the weight of the tara valve (Figure 7b). These results possibly suggest that the higher weight of tara's valves (tannin) is related to the higher Fe contents in the soil. With Fe nano oxide levels (0, 250, 500, 750 and 1000 mg dm^{-3}) in soybean production, the highest yields occurred at 500 mg dm^{-3} [43].

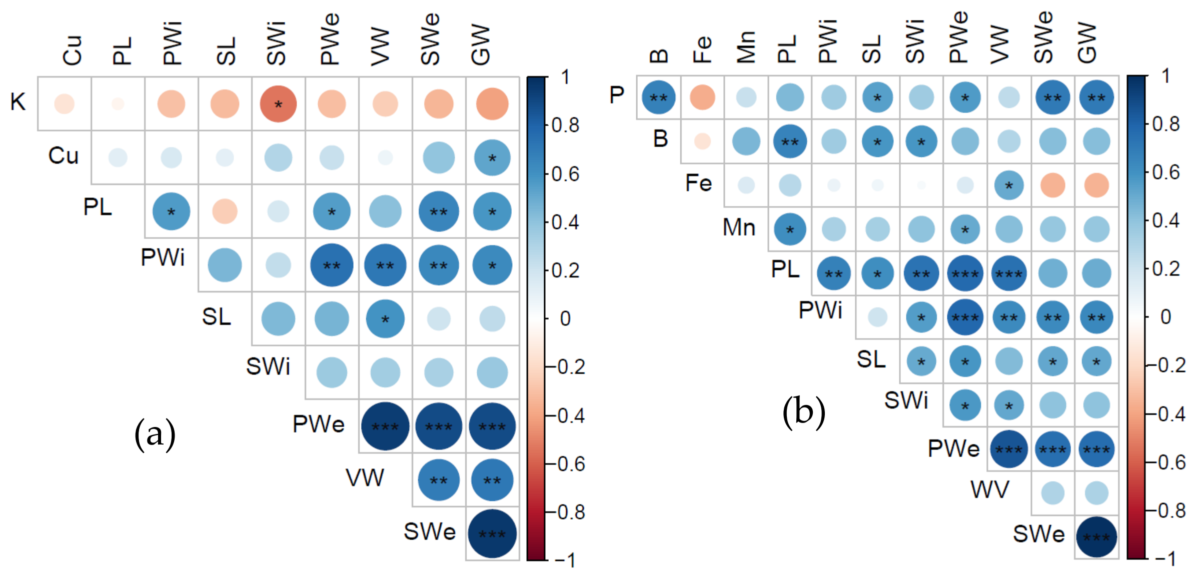

Figure 7. Environment (**a**) natural and (**b**) agroforestry correlation matrix. Pearson's correlation coefficient (r) of potassium (K), copper (Cu), pod length (PL), pod width (PWi), seed length (SL), seed width (SWi), pod weight (PWe), valve weight (VW), seed weight (SWe) and gum weight (GW) of tara. Significance level: * ($p < 0.05$), ** ($p < 0.01$) and *** ($p < 0.001$).

4.3. Influence of Altitude and Temperature on the Dimensions and Weight of Tara Pods

In the regressions in Figures 4 and 6, the dimensions and weights of the pod, valve, seed and gum are higher for the agroforestry environment compared to the natural environment; this is due to human activities carried out in the agroforestry system. Agroforestry activities during the crop cycle are characterized by the preparation and organic fertilization of the soil, sowing, weeding and harvesting of associated crops.

It was determined that the weight of tara pod, valve, seed and gum increases as the altitude increases, while the temperature decreases (Figure S1), in which, at lower temperatures, the commercial maturation time of the pod increases; giving the pod a longer time for the accumulation of photo-assimilates in the valves (tannins) and seeds (gum). In coffee (*Coffea arabica*), [44,45] determined that increasing altitude correlates with an increase in sucrose and nicotinic acid in the fruit. In corn (*Zea mays*), [46] found that increasing the ambient temperature by 1.5 and 3 °C reduced grain yield.

Atmospheric pressure is lower at higher altitudes or at lower temperatures, as a result, the gaseous diffusion (water vapor, CO_2 and O_2) decreases in the tara stomata at higher altitudes (3110 m) compared to the lowest (2020 m); in contrast, to compensate for the low gaseous diffusion, the efficiency of the metabolic process (photosynthesis and respiration) must be higher at higher altitudes, reflecting a higher production of tannins and tara gum. In measurements of the gas exchange of *Nothofagus cunninghamii* at different altitudes (350, 780 and 1100 m altitude), it was determined that stomatal density, carbon assimilation rate, photosynthetic rate and carboxylation efficiency increased with increasing altitude [47].

5. Conclusions

With the increase in altitude or decrease in temperature, the length and width of the pod and seed, and the weight of the pod, valve, seed and tara gum increase, both in natural and agroforestry environments. In addition, association with annual crops and perennial pasture possibly favor the length and width of the pod and seed, and the weight of the pod, valve, seed and gum in the agroforestry environment when compared to the natural environment. Larger pod and seed dimensions and higher pod, valve, seed and gum weights are related with higher soil $CaCO_3$ content in a natural environment and higher soil P and B contents in an agroforestry environment at higher altitudes. Higher Fe contents in the soil probably improve tara's tannin weight (valve) in the natural and agroforestry environment. The productive response of tara, reflected in its weight and size of pods, was higher in an agroforestry environment than in a natural environment. Because of the above, it is important to emphasize that further studies on the production of tara pods are necessary for a better understanding of the interaction with altitude and soil fertility, in order to expand the revenue and employment of small local farmers in the Peruvian Andes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13030646/s1, Figure S1: Mean temperature of the period (MTP), distribution for ten months of the Tara reproductive period in the altitude classes in the altitudinal gradient between 2021 and 3101 m. The mean was accompanied by the bootstrap method's non-parametric confidence interval (CI, 95%); Figure S2: Altitudes in the agroforestry environment of Tara and some soil chemical properties with significant differences. (a) phosphorus (P), (b) potassium (K), (c) boron (B), (d) zinc (Zn), (e) calcium carbonate ($CaCO_3$) and (f) iron (Fe). Mean followed by the bootstrap method's non-parametric confidence interval (CI, 95%); Figure S3: Altitude 3007 m in the natural and agroforestry environment of Tara and some soil chemical properties with significant differences. Cation exchange capacity (CEC) (a), calcium carbonate ($CaCO_3$) (b), phosphorus (P) (c), potassium (K) (d), boron (B) (e) and iron (Fe) (f). The mean was followed by the bootstrap method's non-parametric confidence interval (CI, 95%); Figure S4: Altitudes in the agroforestry and natural environment together of Tara, and some soil chemical properties with significant differences. (a) calcium carbonate ($CaCO_3$) and (b) iron (Fe). The mean was followed by the bootstrap method's non-parametric confidence interval (CI, 95%); Figure S5: Altitudes in the natural environment of Tara and some soil chemical properties with significant differences. (a) zinc (Zn), (b) copper (Cu), (c) manganese (Mn), (d) cation exchange capacity (CEC), (e) calcium carbonate ($CaCO_3$) and

(f) iron (Fe). The mean was followed by the bootstrap method's non-parametric confidence interval (CI, 95%).

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