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A GIS-Based Estimation of Bioenergy Potential from Cereal and Legume Straw Biomasses in Alentejo, Portugal

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Abstract: Portugal exhibits a large deficit in cereals with an import/export ratio of about 18%. Alentejo is a southern vast plain region, which is the largest cereal producer in the country, with about 80% of the total cereal area. The region also shows a huge local energy deficit with a ratio of about 17% between spent and produced energy. In this context, this work used GIS modeling based on available digital geographical information on soil and topographic conditions in Alentejo for estimating optimal production areas of four main classes of cereal and legume classes, which were wheat, barley, oat/lupin, and triticale/broad bean. The estimated areas were validated by 199 sample points in the field and allowed to quantify a potential of bioenergy production from straw biomasses based on yields of biomass net calorific values of 18 MJkg^{-1} and yields of 6, 9, 6, and 9 tons/ha for the four classes in the order indicated. The estimated areas allocated to the cereal and legume classes covered approximately four municipalities in the region. The total modeled area in Alentejo for the four cultivation classes was 44,980 ha. The results showed that even if 50% of the estimated total straw biomass produced was used for animal feed, the estimated bioenergy production of the remaining half biomass would be of about 2940 TJy^{-1}, or about 12.5% of the actual regional energy production, which is an energy amount able to supply 35 organic Rankine cycle (ORC) 2.5 MW cogeneration units and 347 boilers with 125 kW thermal power, delivering renewable electricity to the grid, and heating facilities as diverse as buildings, nursing homes, or horticultural greenhouses. More than 160 kton of CO_2 fossil emissions would also be avoided, delivering a contribution to mitigating effects of climate change. By contributing to the reduction of the large cereal dependence and the carbon emissions of the country, the proposed strategy would contribute to increasing the decentralized bioenergy production for applications in buildings and local facilities, significantly boosting the socio-economic dynamics of rural areas involved.

Keywords: straw biomass; organic Rankine cycle; geographic information systems

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1. Introduction

Agricultural residues, specifically temperate cereal and legume straw biomasses as sub-products of grain production, are surely a potential renewable feedstock for local bioenergy production with potential application in electricity and heat production and in second-generation fuels as well [1]. Traditionally, straw biomasses have been a feedstock considered for combustion, torrefaction, gasification, and carbonization technologies, along with fermentation. These biomass applications contribute thereby to a better equilibrium of greenhouse gas emissions from fossil sources and mitigation of climate change effects.

In Portugal, the development of cultivations of cereals can be envisaged as very relevant, insofar as the ratio of import/export of the country is 18%. Also, considering the set of wheat, rye, oat, barley, and corn, the degree of self-provisioning in the country is about 20%. The national area planted with grain cereals suffered a substantial decrease (above 70% on average) since 1986. Notably, wheat occupied more than 300 thousand hectares, with this area gradually decreasing, being less than 40,000 hectares in 2016, although with higher productivity by unit area [2–6].

The Alentejo region in Southern Portugal concentrates currently most of the production areas of these feed cereals, with about 80% of the total productive area in the country, being an important provider of food products, based on temperate cereal and legume cultivations aiming grain production with a huge yield of biomass from shoot straw residues [7,8]. Alentejo displays a vast undulating and open rolling plain area of about 27,330 km^2, with Mediterranean characteristics and agricultural property specificities in terms of significant areas of individual farms ranging up to tens or hundreds of hectares. This region is also very energetically dependent with a total energy consumption in 2022 of about 143,800 TJ vs. a production of circa 24,500 TJ [9].

Genetic breeding during the second half of the 20th century led in Australia to gains of 0.015 per decade of temperate cereals in harvest index, HI, defined as the ratio of the grain to the shoot dry matter and of 0.02 in the UK. Traditionally, straw biomasses have been a feedstock considered for combustion, torrefaction, gasification, and carbonization technologies, along with fermentation. Typically, power plants and district heating plants use rectangular big straw bales, which can weigh as much as half a ton with a 2.75 m length and a section of about 1.25 m^2. In the Portuguese textile industry, the use of woody biomass instead of natural gas in steam boilers was shown as competitive with savings of 35% by kWh of thermal energy [10].

The average net calorific value for cereal straws, which is usable for combustion purposes, ranges between 16.6 $MJkg^{-1}$ and 20.5 $MJkg^{-1}$, with established industrial mature thermochemical solutions ranging between the following: (i) combustion industrial units as large as, e.g., 150 MWe to 350 MWe with co-firing with pulverized coal, with up to 10% and 20 $tonsh^{-1}$ of straw share at full boiler load [11]; and (ii) organic Rankine cycle (ORC) cogeneration units of heat and power with less than 1MWe power and up to 70% of heat yield, corresponding to up to a supply of a 50 $tonsday^{-1}$ order or magnitude [12,13]; or (iii) boilers for heat production of a smaller scale of 125 kW and energetic efficiency of about 75%, used for hot water supply [14–17]. Straw-heating equipment can be used for heating agricultural facilities, e.g., for livestock, stables, and grain-drying plants. In Europe, in 2019, there were about 370 biomass ORC units [13]. One study showed that in Italy for rice straw, an optimal small-scale ORC solution was based on the production of 100 kWe power and up to 710 kWth thermal energy [18]. Problems related to fouling, slagging, and corrosion of combustion equipment, associated with higher amounts of inorganics, such as potassium, silica, and chlorine, can be bypassed by prior leaching of straw biomass before combustion or by reducing the furnace exit temperature to ranges below the initial deformation temperatures of biomass ashes [11,15,19].

In the EU, the estimations about the annual production of straw residues are about 330 Mton [20]. Also referred to in the literature is the significant interannual variability in EU regions, perhaps higher than 20% in southern countries, on the production of crop residues. This variability is due to factors associated with drivers, such as discrete extreme weather conditions, harvestable area changes linked with agricultural policies, or variations in technical and management factors [20,21]. In Alentejo, the hydrographic basin of the Alqueva dam, with an area of 250 km^2 and allowing for the irrigation of 120,000 ha, can provide a relevant potential contribution to the development of cereal and legume cultivations, allowing for bypassing heat and water scarcity episodes, typical of Mediterranean regions [20].

The biomass productivity per unit area of cereals and legumes, such as oat, triticale, barley, wheat, lupin, and broad bean, is a key variable for establishing mass and energy balances. Reported biomass productivities per unit area for all EU areas of cultivations of wheat, barley, oat, and triticale were 5.9, 4, 4.1, and 5.2 $tonha^{-1}$ [20].

Unkovich et al. [22], for dryland crops in Australia with temperate or Mediterranean conditions, published an extensive review from a dataset with more than 3000 estimates of HI with biomass productivity data of six cereal and legume crops. For wheat, these authors average dry mass yields of 6.7 $tonha^{-1}$ with values up to 22.5 $tonha^{-1}$ and harvest indexes ranging between 0.08 and 0.56. For barley, the same study reports shoot biomass yields higher than those of wheat, with an average of about 8 $tonha^{-1}$ and values up to 19.3 $tonha^{-1}$ and harvest indexes between 0.09 and 0.59. For medium-textured soil in a Chinese site with a typical continental climate and an average annual precipitation of 650 mm, Jin et al. [23] deliver wheat straw biomass productions ranging between 6 and 14 $tonsha^{-1}$. Under typical Mediterranean conditions in Lebanon, with an average annual rainfall of 592 mm, average maximum and minimum temperatures ranging, respectively, between 11.3 °C and 30.7 °C and −2.2 °C and 8.7 °C, Abi Saab et al. [24] refer shoot straw biomass productivities in field trials of barley and wheat, ranging between 6.19 $tonha^{-1}$ and 13.14 $tonha^{-1}$ and 6 $tonha^{-1}$ and 11.7 $tonha^{-1}$, respectively.

For oat, Unkovich et al. [22] refer to the average values of shoot as 9.7 $tonha^{-1}$ with values up to 28.1 $tonha^{-1}$ and HI between 0.11 and 0.48. Tulu et al. [25], in field trials of seven oat genotypes in Ethiopia, found productivities ranging between 6.65 and 11.34 $tonha^{-1}$ and averaging 8.1 $tonha^{-1}$. Asefa et al. [26], from field trials in Ethiopia with 21 oat genotypes, obtained higher productivities ranging between 10.1 and 15.4 $tonha^{-1}$. Pinto et al. [27], from field trials with oat cultivars in Brazil with annual rainfall and temperatures averaging 572 mm and 16.6 °C obtained average productivities of biomass straw of 8.1 $tonha^{-1}$.

For triticale, Unkovich et al. [22] found that the average values for straw biomass productivity were 9.5 $tonha^{-1}$, with values up to 11.23 $tonha^{-1}$ and a harvest index ranging between 0.28 and 0.46. Faccini et al. [28] refer to productivities of straw triticale ranging between 6 and 10 $tonsha^{-1}$ in agrosystems ranging from typical Mediterranean to fertile environments, with yields reaching 18 to 20 $tonsha^{-1}$ and 11–13 $tonsha^{-1}$ under milky-wax maturity, in the same environments. The "milky phase" in triticale cultivation, as in other cereal crops like wheat and barley, is a key developmental stage during grain formation. The same authors refer to another field trial in Italy in 2016, evaluating a total of 15 genotypes, including both registered varieties and advanced breeding lines. The whole plant was harvested at the milky ripening stage when it is almost waxy, with trials producing 17.6 $tonsha^{-1}$ of dry matter ranging between 14.4 $tonsha^{-1}$ and 19.3 $tonsha^{-1}$.

Finally, available information for the lupin and broad bean (*Vicia faba*) legumes, the Australian study of Unkovich et al. [22] reports average productivities of about 5.1 $tonha^{-1}$ for both cultivations, with maximum values of 13.2 $tonha^{-1}$ and 10.74 $tonha^{-1}$. For broad bean, Gómez et al. [29], in Italian field trials, obtained biomass productivities in straw shoot biomass ranging between 8 and 10 $tonsha^{-1}$. Amalfitano et al. [30] obtained shoot straw broad bean productivity yields ranging between 9 and 10.6 $tonsha^{-1}$ in Southern Italy field trials. Natera et al. [31], for blue lupin, *Lupinus augustifolius*, obtained productivity results ranging between 7.6 $tonsha^{-1}$ and 10.2 $tonsha^{-1}$ in field trials in Mexico. For broad bean, in field trials in Czechia, Šimon and Škrdleta [32] obtained productivities in shoot straw biomass ranging between 7.39 $tonsha^{-1}$ and 19.2 $tonsha^{-1}$. For yellow lupin, Perdigão et al. [33] obtained biomass yields of 5 $tonsha^{-1}$ in field trials in Northern Portugal. In particular, the above-ground biomass yield of *Lupinus luteus* in Portugal, harvested 5 months after sowing, has a yield of 4900 to 4930 $kgha^{-1}$ in the first year of cultivation and from 5330 to 6370 $kgha^{-1}$ in the second year of cultivation [34]. Maia et al. [35], for *Lupinus albus* and *Lupinus luteus* field trials in Northern Portugal, delivered biomass productivities of 4.1 $tonsha^{-1}$ and 3.85 $tonsha^{-1}$, respectively.

Another relevant issue related to the production of cereals and legumes is related to the energy necessary for producing cereals and legumes along the lifecycle in the field. One representative review study on this issue is that of Elsoragaby et al. [36]. Energy consumption for crop cultivation includes, e.g., indirect non-renewable energies for manufacturing fertilizers, diesel fuel and electricity for pumping water, and power machinery or indirect energy for manufacturing fertilizers. For wheat and barley, these authors state that these non-renewable energies range between 16,734 and 41,660 $MJha^{-1}$. These energy input amounts corresponded to the potential bioenergy obtainable. For a legume, such as soybean, the same authors mentioned that the energy input was about 23,221 $MJha^{-1}$ and 21% of bioenergy potentially produced. Overall, the same authors mention overall energy ratios of 4.05 and 4.53 for cereal and leguminous crops, respectively, with the energy ratio defined as the ratio indicative of the energy produced per unit of energy utilized.

Besides the potential for biomass and bioenergy production, legume and cereal straws have been traditionally used as forages in animal feed. An equilibrium between cereal and legumes is essential to an adequate healthy animal diet, improving decisively milk and livestock production. Straw feedstuff digestibility is extremely variable and almost lower than that of small grains, depending on the concentration and chemical composition of cell walls which are their main single components [37,38]. The cereal straws, despite some tastiness to cattle, show a lower nutritional quality than legume straws. This is due to lower protein and higher cellulose and hemicellulose polymer fiber amounts in cereal straws, leading to a lower digestibility by comparison with legume straws. Lignin is the other amorphous cross-linked biopolymer of straw biomasses, which increases with plant maturation and secondary growth [39]. This polymer is composed of syringyl (S), guaiacyl (G), and p-hydroxyphenyl (H) units and is critical in reducing forage digestibility, with this restricting effect being smaller in legume forages. The (S/G) ratio is an index variable representative of lignin crosslinking, complementing the lignin amount, for the analysis of the dynamics of biomass biopolymers [40]. Biotechnological efforts have been therefore carried out to reduce cell wall lignification and control lignin composition, e.g., in reducing (S/G) ratio during the beginning of plant secondary growth [37,38,41]. The forage digestibility can be substantially improved through silage. This is a common technique based on the anaerobic bacterial fermentation of straw substrates with the production of lactic acid which hydrolysis of polysaccharides, softening of the cell wall and lignin aromatic structures and producing lactic acid, which improves the palatability of substrates while minimizing mass and nutrient losses [42].

Under all the above contexts, with the present work, we intend to analyze the potential to produce bioenergy in Alentejo from temperate cereal and legume cultivations specially considered as very apt in this region, which are wheat, barley, oat, triticale, lupin and broad bean. A spatial analysis of areas with high suitability for these cultivations, based mainly on soil physical and chemical properties, was carried out along with mass and energy budgets for the main allocated areas. Conditions of no animal feed with straw biomass or use of 50% of total straw biomass for animal feed were considered. The total bioenergy produced was directed for cogeneration units of heat and power with less than 1 MWe power and boilers for heat production of a smaller scale of 125 kW, which should contribute to covering part of the global energy needs in the Alentejo region.

2. Materials and Methods

The six crops chosen for this work were wheat, barley, oat, lupin, triticale, and broad bean, considered very representative of the agricultural landscape of the Alentejo region. The first part of the methodological approach for this work is shown in the diagrammatic scheme of Figure 1, corresponding to the processes used for suitable area extraction and field validation.

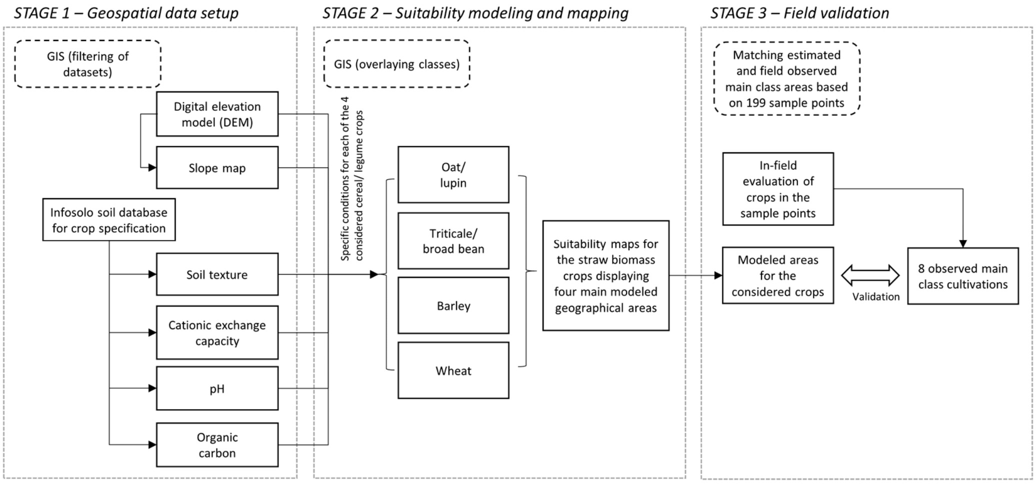

Figure 1. Schematic diagram of the methods used for suitable area modeling and mapping for the chosen cereal/legume crops and field validation.

In the first stage of Figure 1, a geospatial data setup was carried out. The values of the physical and chemical soil properties, which were texture, cationic exchange capacity, pH, and organic carbon, assigned to typify and discriminate the adequacy of soils for these crops, are shown in Table 1. These values resulted from field trials in these species carried out in the Plant Breeding Station Unit in Elvas, Alentejo. Lupin and broad bean soil occupations were considered interchangeable with oat and triticale, due to the similarity of their soil requirements. Physiographic classes of slope and elevation were also considered for the modeling, with respective values lower than 5% and 300 m being a restrictive condition for establishing potential crop areas. An additional condition was that only patches larger than 2 ha were considered for analysis.

Table 1. Assignment of soil chemical and textural composition for four cereals and two legume crops.

Soil Properties	Oat/Lupin	Triticale/Broad Bean	Barley	Wheat
Texture	LSa, SaL [1]	LSa, SaCL [1]	SaL, SaCL [1]	SaL, SaCL [1]
CEC	14 to 20	14 to 20	14 to 20	20 to 26.7
pH	6.3 to 7.1	6.3 to 7.1	7.1 to 8	7.1 to 8
Organic carbon (%)	0.1 to 1.3	1.3 to 4.4	1.3 to 4.4	1.3 to 4.4

[1] Textures: LSa—loamy sand; SaL—sandy loam; SaCL—sandy–clay–loam.

In this context, the spatial datasets used in the first stage were as follows: (i) The Infosolo Legacy Database [43], representative of data from 3461 soil profiles established between 1966 and 2014, with data on soil pH, organic carbon content, textural composition for soil taxonomy, and cation exchange capacity. These data are mapped in Figure 2; (ii) ESA's EU-DEM v1.1 Digital Elevation Model with a spatial resolution of 25 m [44] for the inclusion of slope and elevation constraints; and (iii) the Portuguese official land use/land cover map for 2018 [45], a thematic polygon map based on photointerpretation and with a hierarchical 5-level nomenclature with more than 80 classes. All this geospatial information was gathered and combined with a geographic information system, ArcGIS Pro 3.1.

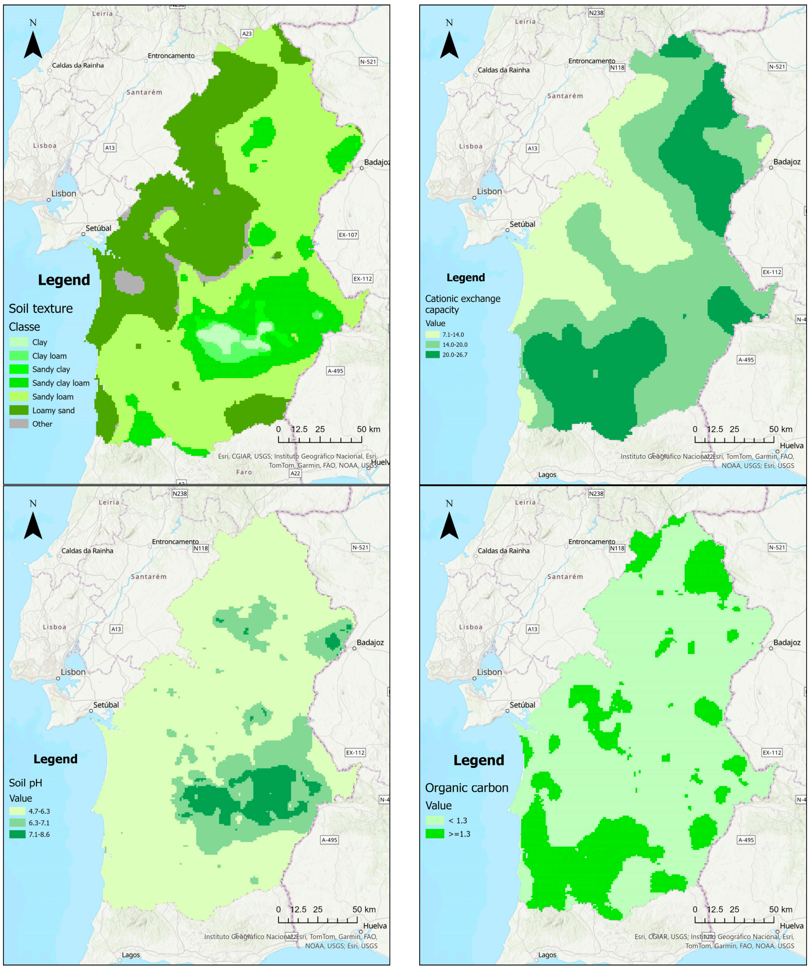

Figure 2. Maps of soil texture (**top left**), cationic exchange capacity (**top right**), soil pH (**bottom left**), and organic carbon (**bottom right**) for the Alentejo region.

The second stage involved the processing of the geospatial data to obtain suitability maps for the considered cereal/legume crops, using the same GIS software. Map overlaying enabled the identification of four main geographical areas more representative of the distribution of each of the chosen cereal and/or legume crops.

In the third stage, the estimated areas were subjected to a validation scheme analysis of land use in 199 field points sampled within the locations obtained in the second stage. The mentioned minimum area restriction for patch areas, 2 ha, was used. The sampled points fell into the area delimitated by WGS84 geographic coordinates 37.594° N and 38.418° N of latitude and 7.390° W and 8.213° W.

Figure 3 corresponds to the subsequent process of evaluating the mass/energy balances of the chosen crops in the selected areas. It shows the modeling processes used to estimate mass and energy balances of the chosen cereal/legume crops in the main representative estimated geographical areas, considering each of the 16 combinations of four crops and four main selected geographical areas mentioned below. For local bioenergy production, two main straw biomass applications were proposed, which were heat and power co-generation under ORC 2.5 MW units and 125 kW boilers for heat production. Two alternative scenarios were considered: the first with straw, aiming 100% for bioenergy, and a second with 50% for bioenergy and 50% for animal feed use.

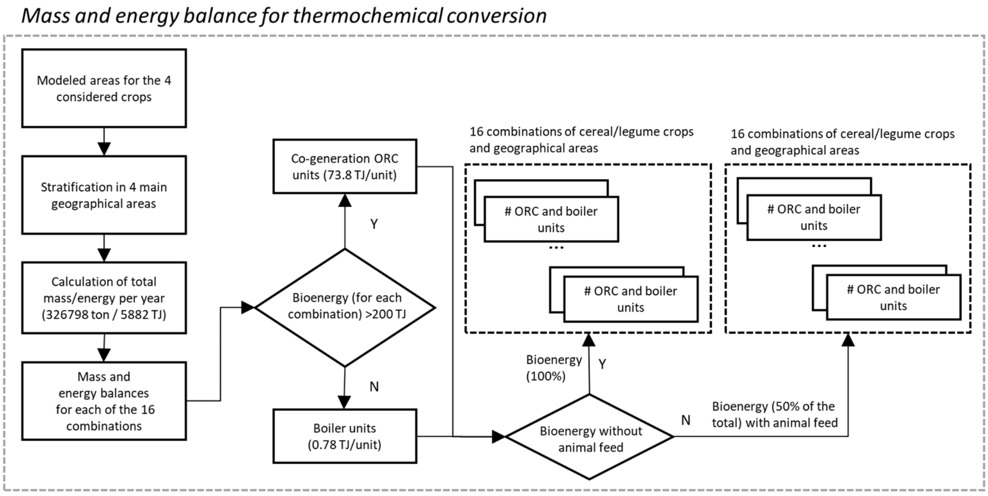

Figure 3. Mass and energy balances for thermochemical conversion.

3. Results and Discussion

The suitable areas found for the four cereal/legume classes are indicated in Table 2 and mapped in Figure 4. It can be noticed that a prevalence was established for oat/lupin and triticale/broad bean pairs with 16,045 ha and 17,383 ha, respectively. As mentioned above, the assignment of soil conditions assumed overlapping areas to lupin and broad bean and oat and triticale, respectively, due to similarities in soil requirements for the legume crops with these cereals. The total modeled potential cereal area for Alentejo was 44,980 ha, which can be compared to totals of actual occupied areas of about 89,472 ha for the whole country in the period between 2019 and 2023 if considered that about 80% of these cultivations were located in the region.

Table 2. Areas (in hectares) of the cereal and legume crops for slopes lower than 5% and elevations lower than 300 m.

	Oat/Lupin	Triticale/Broad Bean	Barley	Wheat
Slope < 5%, Elevation < 300 m	16,045	17,383	1587	9965

The modeled areas, corresponding to good soil productive conditions in Alentejo, compared to total soil occupation areas in the country for oat, triticale, barley, and wheat in 2015 of 49,400 ha, 21,600 ha, 20,100 ha, and 35,800 ha, respectively. These area results, coupled with available information on productivity, calorific power, and straw yield, allow for the establishment of mass and energy balances [7,46,47].

The results of field validation in the 199 sampled points are posted in Table 3. For practical effects, related to the yearly variability of real annual cultivations, the observed cultivations in the field were grouped into eight classes, which, besides individual oat (8 points), barley (5 points), wheat (7 points), and triticale (2 points), included forage intercropping (50 points), breeding pasture (3 points), tilled soils (6 points), and natural pastures (118 points). Table 3 shows that, despite few direct correspondences, a potential match between the chosen and observed cereal classes was verified, due to the preponderance of forage intercropping or natural pasture soil use classes. The former was an aggregated class, including patch points with at least one of the four initial cereal classes, and the latter was a class where neither any sown was applied nor possible plant sowings did thrive due to lower rainfall in Alentejo in the years 2022 and 2023. Indeed, the annual accumulated rainfall in Alentejo in these years corresponded to 75% and 50% of the average of the period between 1981 and 2010.

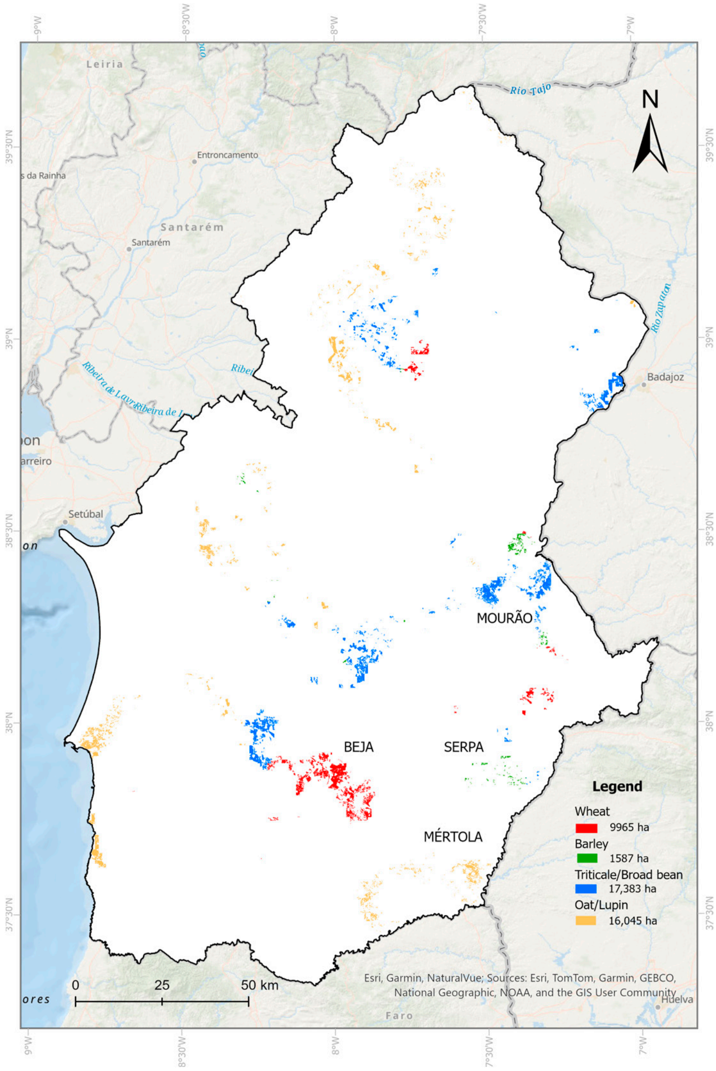

Figure 4. Suitability map for the selected cereal and legume crops in Alentejo areas with slopes lower than 5% and elevations lower than 300 m.

Table 3. Correspondences between initial and observed cereal classes in field points sampled in 2023.

Observed Cultivation	Number of Field Points Matching One of the Four Soil-Use Groups	Matched Initial Classes
Barley	2 3	Wheat Triticale
Oat	1 4 3	Oat/lupin Barley Triticale
Wheat	2 5	Oat/lupin Wheat
Triticale	1 1	Oat/lupin Barley
Forage intercropping	10 11 13 16	Oat/lupin Barley Wheat Triticale

Table 3. *Cont.*

Observed Cultivation	Number of Field Points Matching One of the Four Soil-Use Groups	Matched Initial Classes
Bred pasture	2 1	Barley Triticale
Natural pasture	39 18 24 37	Oat/lupin Barley Wheat Triticale
Tilled soil	4 2	Triticale Wheat

In Portugal, the spring of 2023 was the third driest since 1931, and the accumulated rainfall of 100 mm corresponded to about 50% of the normal value. This fact is related to the actual climate change context, with a real impact in the Mediterranean basin [48,49]. This lack of precipitation in 2022 and 2023 and its negative impact on the feasibility, survival, and thriving of sown annual winter cultivations contributed to the typical interannual variability of cereal production areas in Southern Europe referred to in the Introduction and therein to a high number of sampled points with forage intercropping and natural pasture occupations, which matched the proposed four soil use cereal classes.

Table 4 shows the results for the spatial modeling of biomass production in terms of occupation areas of the four cereal/legume classes, with a prevalent stratification of these classes in four main geographical areas. A total of sixteen combinations of four crops and four geographical areas was therefore considered. The four geographical areas cover approximately the municipalities of Beja, Serpa, Mourão, and Mértola and hereafter were named after them.

Table 4. Areas for spatially modeled cereal and legume occupations in four major geographical areas.

	Beja	Serpa	Mourão	Mértola
Wheat	7879	1854	232	0
Barley	0	873	714	0
Oat/lupin	917	0	917	14,211
Triticale/broad bean	5650	2607	9126	0
% of total areas	32%	12%	24%	32%

It can be noticed that triticale/broad bean and oat/lupin were the cultivations whose areas were higher, with 17,383 ha and 16,045 ha, respectively. Wheat and barley areas followed with 9965 ha and 1587 ha, respectively. Triticale/broad bean areas were spread by regions of Mourão, Beja, and Serpa, while oat/lupin prevailed in Mértola with 14,211 ha. Wheat areas were higher in Beja and Serpa, with 7879 ha and 1854 ha, respectively. On the other hand, the cereal occupation areas of Beja, Mértola, and Mourão were the highest, with 14,445 ha, 14,211 ha, and 10,998 ha, respectively, followed by Serpa with 5334 ha.

Straw biomass production was calculated based on dry matter productivities of 6, 9, 6, and 9 tons/ha for wheat, barley, oat/lupin, and triticale/broad bean, respectively, delivering total dry biomass yearly productions of 326,790 tons, corresponding to 59,790 tons, 14,283 tons, 96,270 tons, and 156,447 tons for these classes. The distribution of the cereal/legume productions per geographical area is given in Table 5. It can be seen that the Beja area showed the highest proposed cereal production, with 103,622 tonsy^{-1}, followed by Mourão and Mértola and with the Serpa zone ranking last with 42,446 tonsy^{-1}. Mértola and Mourão were the zones where one single class (which was oat/lupin), and four plant classes were proposed, respectively. In Beja and Serpa, three plant classes were proposed, which were wheat and triticale/broad bean in both and oat/lupin and barley in Beja and Serpa, respectively.

Table 5. Productions (tonsy^{-1}) for cereal and legume occupations in the four geographical areas.

	Beja	**Serpa**	**Mourão**	**Mértola**
Wheat	47,276	11,123	1390	0
Barley	0	7855	6427	0
Oat/lupin	5501	0	5501	85,267
Triticale/broad bean	50,845	23,467	82,134	0
Total production	103,622	42,446	95,453	85,267
% of total production	32%	13%	29%	26%

The total proposed production of bioenergy in the four zones was 5882 TJy^{-1}, based on a net calorific value (NNV) of 18 MJkg^{-1}, and its distribution by geographical areas is indicated in Table 6 and Figure 5. These distributions agreed obviously with those of plant cultivation areas shown in Table 5.

Table 6. Bioenergy production (TJy^{-1}) for cereal and legume occupations in the four geographical areas.

	Beja	**Serpa**	**Mourão**	**Mértola**
Wheat	851	200	25	0
Barley	0	141	116	0
Oat/lupin	99	0	99	1535
Triticale/broad bean	915	422	1478	0
Total production	1865	764	1718	1535

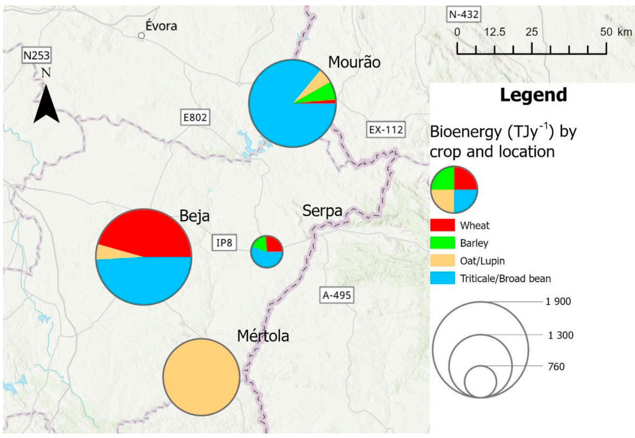

Figure 5. Bioenergy production (TJy^{-1}) for cereal/legume occupations in the four geographical areas.

The total bioenergy amount of 5880 TJy^{-1} estimated in the Alentejo region with this modeling is very significant, corresponding to about 25% of the abovementioned regional energy production of 24,500 TJ in 2022. Also, annual amounts of about 329 kton CO_2 and 435 kton CO_2 emissions of fossil natural gas and diesel with CO_2 emission factors of 56 kgCO_2GJ^{-1} and 74.1 kgCO_2GJ^{-1}, respectively, would be avoided in the region by application of this renewable additional bioenergy, which comes directly from the carbon stored in straw biomass. These carbon savings from bioenergy use compensate for the possible carbon loss in soils due to the removal of straw of annual cultivations from the land [18]. Additional practical solutions for compensation for a lack of carbon storage in the soil can be the growing of cover crops after harvest with further incorporation in the soil [18,50].

Despite that growing cereal and legume crops are a sink for atmospheric CO_2, the release of this assimilated carbon is largely dependent on complex factors related to the management of harvested straw biomass. Annual agricultural crop systems are dynamic and sensitive to annual environmental variations [20].

The proposed alternatives for regional energy production were cogeneration for heat and power in 2.5 MW ORC cogeneration units, delivering 70% energy for heat and 20% power and 125 kW boilers for heat production through hot water, with a 75% efficiency. The yearly bioenergy inputs from biomass straw needed for each ORC and boiler unit were 73.8 TJ and 0.98 TJ, respectively. A threshold of 200 TJ by pair combination of plant cultivation and zone was considered as an upper limit for the use of 125 kW boilers, with ORC units established in pair combinations of plant cultivation and zone with higher energy amounts.

The results for the establishment of both energy applications are shown in Table 7 and Figure 6. The total numbers of 2.5 MW ORC and 125 kW boiler units were 71 and 694, respectively. The use of 50% of straw biomass for animals will reduce the estimated bioenergy production and units by half, with 2941 TJy^{-1} of total produced bioenergy and 35 and 347 ORC units and boilers, respectively. In this case, an amount of as much as about 12.5% of the energy regional production would still be achieved.

Table 7. Units proposed for the combinations of cultivations and geographical areas.

	Beja	Serpa	Mourão	Mértola
Wheat	12 ORC cogeneration units	204 boiler units	26 boiler units	0
Barley	0	144 boiler units	118 boiler units	0
Oat/lupin	101 boiler units	0	101 boiler units	21 ORC cogeneration units
Triticale/ broad bean	12 ORC cogeneration units	6 ORC cogeneration units	20 ORC cogeneration units	0

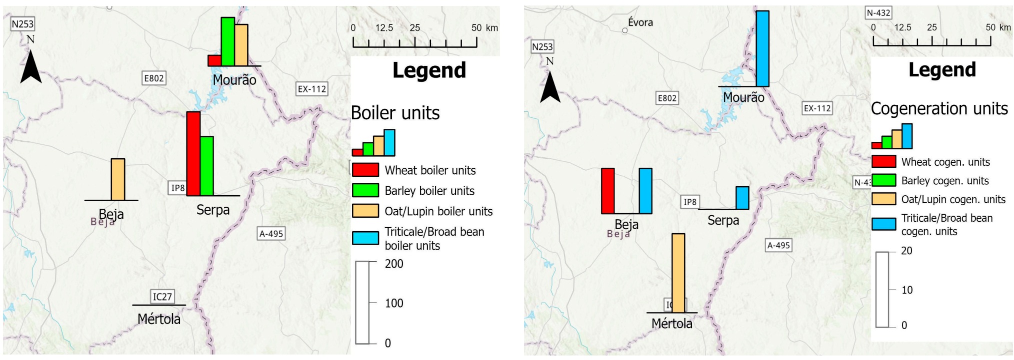

Figure 6. Proposed energy units for the combinations of plant cultivations and geographical areas: boiler units (**left**) and ORC cogeneration units (**right**).

The two bioenergy production modalities correspond to a decentralized strategy, by considering the proximity of biomass conversion with the geographical distribution of biomass production, along with the contribution of bioenergy to boost the socio-economic networks of rural communities. The bioenergy produced can indeed be applied in the heating of facilities as diverse as schools, hotels, nursing homes, hospitals, small industrial units, or horticultural greenhouses [11,13]. The electric power produced through ORC systems can be fed into the local grids. The whole bioenergy can be subjected to carefully planned small district systems, with supply and demand energy assessments of temporal and geographical peaking variability of energy needs by individual consumers, buildings, public institutions, or local industrial or agricultural facilities. The locations of cogeneration and boiler units should be optimized for further reductions in CO_2 due to straw bale transportation from farm gates to conversion units. For bioenergy production and use, the implementation of this strategy would require environmental, industrial, and agricultural policies aiming to adequately support the decarbonization of the economy at national and regional levels. The policy interventions should be evenly focused on each component of cluster lifecycles, under a cradle-to-grave approach [1,17,21].

ORC cogeneration is a promising technology traditionally applicable for geothermal applications, based on the conventional Rankine cycle with organic working fluids, instead of water, used as operational fluids with lower boiling and critical temperatures and critical pressure delivering a higher efficiency in power production [11,13,15]. These mild operative conditions allow for the production of electricity from a lower-temperature heat source with higher thermodynamic efficiency in a modular unit where the thermodynamic component with a simpler biomass combustion chamber. Financial feasibility is thereby improved by the employment of cheaper materials with lower maintenance costs. The lifetime of this equipment is 20 years with an electricity production cost of about 0.0275 € $kWhr^{-1}$ [12]. The application of the ORC units in district heating, following a prevailing tendency in Europe, would allow for the local thermal agent to consume the cogenerated electricity produced.

The use of automatic boilers for biomass combustion with energy efficiencies as high as 80% to 85% is sufficiently characterized for common use, and biomass has been proven as a competitive source of thermal energy by comparison with natural gas or electricity. The tendential replacement of fossil fuels by biomass renewable sources of energy is in this way facilitated. Neighborhood heating from a few to up to 70–80 homes are two possible modes of network heating through the employment of straw biomass boilers, according to the prevailing circumstances [17]. Farmers individually or within associations can invest in boilers on scales larger than what is necessary for their needs and deliver cheaply the excess heat to their neighbors.

To the best of our knowledge, no other studies have been carried out about the utilization of straw biomass for bioenergy production through thermochemical conversion in Alentejo [7]. Two studies of local utilization of forest and agriculture biomass residues for bioenergy applications in the Alentejo municipalities of Marvão and Estremoz have been presented, clearly demonstrating the financial and environmental advantages of the replacement of diesel and fossil electricity systems into hotel and four school types, respectively [51,52]. General studies exist on items such as densification or electricity production by use of agroforestry residues in large industrial units [53], energy recovery from olive pomace, a relevant biomass resource in Alentejo [53,54], circularity of biomass resources [55], or about the biomass use for electricity production in general [56]. An integrated review lifecycle analysis of the potential bioenergy production through short rotation coppice (SRC) cultivations with the assessment of productivity [57], followed by evaluation of the potential impact of poplar and eucalypt SRC cultivations, provided estimations of about 82,000 ha for total area in the region, corresponding to circa 22,300 TJ of yearly bioenergy delivered [58].

Denmark is an excellent case study of a global leader in the production of bioenergy from biomass straw, and as recently as 2020, this feedstock accounted for more than 2% of the gross energy consumption and about 10% of the renewable energy production [14,17,59]. In this country, biomass straw is used as fuel in items as diverse as district heating plants, cogeneration of heat and power, or at individual farm plants. The Danish case study shows clearly that straw combustion is a mature technology and is currently a viable solution for decentralized carbon-neutral heating and electricity production.

Climate variables are fundamental drivers of agricultural production of food and biomass, and thus, global heating, drought, and extreme weather episodes clearly affect crop productions. Seasonal and long-term climate variability affect these productions in all phases of plant growth, through multiple direct and indirect pathways. Heat or drought can reduce crop yield by limiting carbon assimilation or carbon loss through stomatal activity regulation. Atmospheric temperatures higher than optimal directly affect the balance between respiration and photosynthesis with anticipation and acceleration of the plant phenological stages and reduction in final yield [48,60]. On the other hand, higher temperatures indirectly increase atmospheric evaporative demand for water and reduced crop use efficiency, cause damage on plant tissues or cell membranes and proteins, and influence the occurrence of pest and diseases. High temperatures in plant early growth can contribute to a reduction in leaf sizes and photosynthetic capacity and, in later growth stages, to a decrease in number and size of produced kernels. The high-temperature effects in plants can be reinforced under drought events, wherein water stress increases. Irrigation attenuates the effects of heat and water stresses, thereby minimizing considerable annual yield losses [49,60,61].

Lower straw cereal yields related with extreme weather events in European countries in the first decade of the 21st century, and particularly in the extreme dry year of 2003, were reported in France and Italy [48,61–63]. In Denmark, the effects of climate change on the stability and security of straw production were particularly felt in 2018 when, due to a severe drought, production declined from an annual average of 5.5 Mtons in the period 2013–2019 to just 4 Mtons. In Alentejo, the large abovementioned hydrographic basin of the Alqueva dam, allowing for the irrigation of 120,000 ha, can stabilize the effects of water scarcity in plants due to drought episodes, typical of Mediterranean regions. The Danish case is also demonstrative of how a reduction in fossil fuel consumption can be achieved with the use of straw combustion in Europe where the feedstock is tendentially excessive.

In a practical nutshell, this study, based on a soil profile of four cereal and legume cultivations and an edaphic digital geographic information database, assessed the economic and environmental relevance that these cultivations would assume for bioenergy production in a regional area of 44,980 ha. The bioenergy production from biomass straws would complement the major nutritional goals of grain production and cattle feeding. Installation of cogeneration and boiler units, within the alternatives of 50% use of the straw biomass for cattle feed and 50% of bioenergy vs. bioenergy only, would surely contribute to boosting the microscale economies of the rural communities, derived from the consumption of locally produced biomass residues under principles of decentralization, circularity, and sustainability.

4. Conclusions

In this study, a modeling of the bioenergy production potential from six cereal and legume cultivations was carried out in the Alentejo region in Southern Portugal, with a GIS-based estimation of potential areas based on the physical and chemical soil requirements of these crops. The cereals were wheat, barley, oat, and triticale, and the legumes were lupin and broad bean. Lupin and broad bean were considered as interchangeable with oat and triticale, due to the similarity of their soil requirements, thereby allowing for a set of four crops. The area estimation used soil and topography digital datasets which were overlaid, delivering uneven areas of the cultivation classes covering approximately the municipalities of Beja, Serpa, Mourão, and Mértola. The estimated areas were subjected to field validation in 199 points. Mass and energy balances for straw biomasses were established, assuming yields of 6, 9, 6, and 9 $tons ha^{-1}$ were considered for the four classes in the indicated order, along with biomass net calorific values of 18 $MJ kg^{-1}$. The total modeled potential area for Alentejo for the four cultivation classes was 44,980 ha. Two alternatives of use of biomass for the bioenergy exclusively and of 50% for animal feed were considered. The total bioenergy estimated without animal feed was 5882 $TJ y^{-1}$, an amount corresponding to about 25% of the total energy produced in Alentejo in 2022. Considering the application of 50% of straw biomass for animal feed, the bioenergy produced would be half of the total value. For local exclusive bioenergy production, the alternatives proposed were 71 units of heat and power co-generation under ORC 2.5 MW and 694 units of 125 kW boilers for heat production. The corresponding annual avoided fossil CO_2 emissions would be higher than 320 kton, delivering thereby a circular contribution to an atmospheric neutral carbon budget. Besides the contribution to the reduction in the large cereal dependence of carbon emissions of the country, the proposed strategy would contribute to increasing the decentralized bioenergy production for application in local facilities and buildings, significantly boosting the socio-economic dynamics of these rural communities.

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