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# Searching for the Profitability of Energy Crops: An Agroecological–Economic Land Use Suitability (AE-landUSE) Model

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**Abstract:** The current geopolitical and energy market instability calls for speeding up the EU clean energy transition to increase energy security in all the European regions and make Europe the first climate-neutral continent by 2050. Among renewable energies, modern bioenergy is a promising near-zero-emission fuel for increasing energy security in the heating, electricity and transport sectors while promoting growth and job creation, especially in rural areas. In such a context, energy crops will continue to play a key role. Since agricultural planning is a complex issue, especially when energy crops could compete with food ones, we propose an agroecological–economic land use suitability model (AE-landUSE model) to promote the sustainable use of land resources. The AE-landUSE model was developed by integrating cost–benefit analysis (CBA) and land use suitability analysis (LSA) within geographic information systems (GISs). Tested in the Basilicata region (Southern Italy), comparing two different energy crops (rapeseed and cardoon), the results show the model's utility in identifying suitable areas for energy crops where the investments will be cost-effective. The proposed model will help decision-makers in energy-agricultural planning to increase energy security sustainably.

**Keywords:** water–energy–food nexus; cost–benefit analysis; benefit–cost ratio; geographic information system (GIS)



**Citation:** Viccaro, M.; Romano, S.; Rosalia, I.; Cozzi, M. Searching for the Profitability of Energy Crops: An Agroecological–Economic Land Use Suitability (AE-landUSE) Model. *Environments* **2024**, *11*, 91. https://doi.org/10.3390/environments11050091

Academic Editor: Guobin Fu

Received: 1 March 2024
Revised: 19 April 2024
Accepted: 26 April 2024
Published: 29 April 2024



## 1. Introduction

"*Everything should be made as simple as possible, but not simpler*" (Albert Einstein)

Bioenergy is the world's largest source of renewable energy, and it is expected to grow substantially as one of many complimentary pathways to support decarbonization initiatives to limit global warming to 1.5 °C [1,2]. The IEA roadmap "Net Zero by 2050" recognizes bioenergy as an essential option in the transition towards a carbon-neutral society while simultaneously contributing to the United Nations Sustainable Development Goals (SDGs) [1].

For the European Union, bioenergy will play a crucial role in meeting the newly established binding target of integrating at least 42.5% renewable energy sources into the overall energy mix by 2030, contributing to the EU policy objective of reducing $CO_2$ emission by at least 55% by the same year. In the current global scenario, characterized by geopolitical and energy market instability, bioenergy production is also perceived as a means for the EU to reduce its dependence on external energy supplies, thus improving the security of energy supply in the medium and long term.

In such a context, cultivating dedicated species for energy production, the so-called energy crops, will play an important role [3]. Despite concerns about the environmental impact of energy crop expansion, mainly associated with direct and indirect land use change and food competition for resources [4], various authors have highlighted the possibility of sustainably integrating energy crops into current farming systems. For example, this can be achieved by dedicating marginal lands [4–6] or adopting conservation agricultural practices [7], such as crop rotation [8]. In this regard, Vera et al. [4] have emphasized the importance of considering context-specific conditions in developing appropriate solutions to meet the worldwide demand for sustainable bioenergy. For this reason, researchers are increasingly focusing on optimizing the allocation of energy crops within conventional agricultural systems to minimize the competition with resources used for food production (i.e., land, water, energy); different methodologies have been proposed to aid landscape planners, policymakers, and decision-makers in the thoughtful integration of energy crops into sustainable farming projects [9–15].

In recent years, land suitability analysis within geographic information systems (GIS-LSA) has gained popularity for determining suitable locations for energy crops [3,5,16–20]. Considering crop needs and land characteristics, GIS-LSA assesses how well the qualities of a land unit align with the requirements of the specific land use [21]. However, relying solely on GIS-LSA for analyzing energy crop expansion based only on crop-specific factors may overlook the broader sustainability aspects of land, water and energy resources. The challenge, known as the "land, water, and energy trilemma", underscores the need for a comprehensive and integrated methodological framework to ensure holistic and sustainable resource management. In this framework, Viccaro et al. [15] proposed a spatially explicit model for assessing the scale of impacts on land, water and energy inputs associated with expanding energy crop cultivation, integrating GIS-LSA with the water–energy–food nexus (WEFN) approach [22]. Recognized by the Food and Agricultural Organization (FAO) as a valuable approach for assessing the sustainability of energy projects in agriculture [23], the WEFN makes it possible to systematically address water–energy–food interactions and promote efficient resource use and sustainable development [22,24,25]. Initially focused on water, energy and food, the approach has expanded to include broader issues, including climate change (e.g., water–energy–food–carbon nexus) [26,27] and land management (e.g., land–water–energy–food nexus) [13,28]. Among the different factors affecting the land–water–energy nexus, several authors highlight that economic aspects should not be neglected in nexus assessments [9,13,15,29]. Recently, the profitability of energy crops has not received the same attention as environmental sustainability issues, even though energy crop expansion depends on their economic feasibility even when land, water and energy resources are used efficiently. In GIS-LSA studies, different economic factors have been considered (e.g., infrastructure, equipment, labor); however, their inclusion in terms of presence/absence in land use suitability assessment for energy crops does not provide information on economic feasibility in terms of costs and benefits as a reference point for farmers.

Developed for the first time in the 1930s, cost–benefit analysis (CBA) has been widely utilized in the scientific literature to assess the cost-effectiveness of both public and private investments [30]. In agriculture, by comparing the benefits and costs over a specified time horizon, CBA provides insights into the potential returns on investment and allows farmers to efficiently prioritize and allocate resources among competing agricultural projects or interventions [7]. In the bioenergy context, Cozzi et al. [31] carried out a CBA to assess the economic feasibility of Short-Rotation Forestry (SRF) in a GIS-LSA framework, and Pulighe and Pirelli [9] did so to evaluate the sustainability of biofuel crops in a WEFN framework. In such studies, however, CBA is not spatially explicit, meaning that the spatial variability of factors affecting the economic feasibility of energy crop cultivation is not considered, particularly the spatial variability of crop productivity. While factors affecting costs (i.e., cultivation techniques) may be regarded as the same across a given area, factors influencing benefits (i.e., crop yields) usually may exhibit significant spatial variability due to specific local conditions (e.g., climate and soil conditions). This can bring about a difference in the scale of impacts on the economic feasibility of energy crops and, consequently, on their expansion potential in a given area. For instance, in Cozzi et al. [31], the SRF potential within the study region is delineated based on lands exhibiting high suitability after a CBA; in that study, the data on crop productivity used in the CBA were sourced from the literature. In such cases, the results may lead to misleading conclusions regarding the actual potential of energy crop cultivation. Different productivity levels could exist across the area compared to those considered, resulting in either lower or higher potential than suggested, especially when only considering lands with the highest suitability levels. Excluding areas with moderate suitability levels could limit energy crop expansion. To address these limitations, Viccaro et al. [32] implemented a site-specific approach to assess the cost-effectiveness of SRF fertigated with urban wastewater, carrying out a CBA starting from the concept of biomass productivity and water use efficiency (WUE) [33,34]. The productivity of SRF was spatially determined by multiplying the crop's WUE by the water utilized by the plants. However, similarly to the previous study, the authors constrained their analysis only to lands exhibiting the highest level of suitability to mitigate investment risks. According to the FAO suitability classes [21], only the highly suitable class (S1) presents "*Nil to minor negative economic . . . outcomes*"; the other classes could potentially entail negative economic outcomes ranging from moderate to very high risks (see Table A1). In such a context, a decision support tool is necessary to assist farmers in effectively allocating energy crops by considering their economic feasibility to mitigate the risk of financial loss.

Based on the above, we propose an agroecological–economic land use suitability model (AE-landUSE) that integrates cost–benefit analysis and land use suitability analysis within geographic information systems. By considering multiple criteria simultaneously (agroecological and economic ones), the model identifies suitable areas for energy crops where the investments are cost-effective. In previous studies, CBA has usually been carried out separately from GIS-LSA, resulting in different indices for decision-making. Instead, by combining CBA and GIS-LSA in a single model, AE-landUSE provides a single spatially explicit indicator that aids decision-makers in locating energy crops within the existing agricultural systems. The results are a starting point for conducting a land–water–energy nexus analysis to allocate land, water and energy resources efficiently.

The Basilicata region (Southern Italy) was chosen as a case study for testing the model, considering two energy crops, namely, (i) rapeseed (*Brassica napus* L.), the main biofuel crop in Europe [7], and (ii) cardoon (*Cynara cardunculus* L.), as potential energy crops for Mediterranean environments [35]. This paper is structured as follows: the AE-landUSE model and the case study are described in Sections 2.1 and 2.2, respectively; the main results are presented and discussed in Section 3; and final remarks and suggestions for future research are provided in Section 4.

## 2. Materials and Methods

### *2.1. The Agroecological–Economic Land Use Suitability Model*

Economic feasibility is one of the most important aspects for farmers when planning energy crop cultivation within the current agricultural systems [7]. For this reason, the agroecological–economic land use suitability model was developed starting from the spatial definition of the benefit–cost ratio [30]. The benefit–cost ratio is an indicator used in cost–benefit analysis to evaluate the profitability or economic feasibility of a project, policy or investment. It represents the ratio of the total benefits derived from an investment to the total costs incurred over a specified time horizon.

The benefit–cost ratio ($B/C_j$) can be spatially defined as:

$$\frac{B}{C}_j = \sum\nolimits_{i=0}^{n} \frac{B_{ji}}{(1+r)^n} / \sum\nolimits_{i=0}^{n} \frac{C_{ji}}{(1+r)^n} \quad (1)$$

where $B_{ji}$ and $C_{ji}$ are, respectively, the benefits and costs in period $i$ for each land unit $j$; $r$ is the discount rate; and $n$ is the life cycle of the investment (in years).

The cost-effectiveness of the investment is verified if $B/C_j > 1$, namely, when benefits outweigh costs; conversely, $B/C_j < 1$ indicates that the costs exceed the benefits, suggesting that the investment may not be financially feasible or economically justified. Comparing different investments, the one with the highest $B/C_j$ is to be preferred.

In assessing the profitability of investments related to energy crop cultivation, costs refer to the total production costs (e.g., land preparation, harvest, etc.); for a given crop, these costs depend on specific cultivation techniques and typically do not exhibit spatial variability within the same area. Regarding benefits, these are determined by the prices ($p$) paid for the yields ($Y_j$) after harvest:

$$B_j = p \times Y_j. \tag{2}$$

Since yields usually show high spatial variability, benefits do the same.

Starting from the concept of water use efficiency (WUE) [32,34], $Y_j$ can be spatially calculated as:

$$Y_j = W_{used\,j} \times WUE \tag{3}$$

where $W_{used\,j}$ (water used by the plant) is equal to:

$$W_{used\,j} = Re_j = fc_j\left(1.253 \times R_j^{\,0.824} - 2.935\right) \times 10^{0.001ET_{cj}} \tag{4}$$

in rainfed conditions, and equal to:

$$W_{used\,j} = Re_j + IWR = ET_{cj} \tag{5}$$

in irrigated conditions, with:

$Re_j$ the effective rainfall (mm), namely, the part of the rainfall which plants effectively use;
$fc$ the correction factor depending on soil moisture (for the present study, it is assumed to be 1, which is the value in standard soil conditions);
$R$ the total monthly rainfall (mm);
$ET_{cj}$ the crop evapotranspiration, calculated by multiplying the reference crop evapotranspiration ($ET_0$) by the crop coefficient ($K_c$);
$IWR_j$ the irrigation water requirement, calculated as the difference between $ETc_j$ and $Re_j$.

However, it could be considered that various factors, such as climate and soil ones, as well as cultivation techniques, can significantly impact the crops' WUE and, consequently, the crops' yields [36] (e.g., suitable local conditions can lead to higher yields due to more efficient water use). Considering that land use suitability ($S_j$) in agriculture is a function of the agroecological conditions of a given area $j$ [21]:

$$S_j = f(c_j, s_j, \ldots) \tag{6}$$

with $c_j$ climate, $s_j$ soil, …,the yields $Y_j$ obtained from Equation (3) can be adjusted by multiplying with $S_j$:

$$Y_{adj_j} = Y_j \times S_j = W_{used\,j} \times WUE \times S_j. \tag{7}$$

So, changing $Y_j$ with $Y_{adj_j}$ in Equation (2), our AE-landUSE model can be defined as:

$$\frac{B}{C}_j = \sum_{i=0}^{n} \frac{\left(p \times Y_{adj}\right)_i}{(1+r)^n} \Big/ \sum_{i=0}^{n} \frac{C_{ji}}{(1+r)^n} \tag{8}$$

namely,

$$\frac{B}{C}_j = \sum_{i=0}^{n} \frac{\left(p\left(W_{used\,j} \times WUE \times S_j\right)\right)_i}{(1+r)^n} \Big/ \sum_{i=0}^{n} \frac{C_{ji}}{(1+r)^n}. \tag{9}$$

The AE-landUSE model, as defined, provides a spatial explicit benefit–cost ratio indicator able to evaluate the economic feasibility of energy crop cultivation based on the land suitability levels ($S_j$).

Regarding $S_j$, various methodologies have been proposed in GIS-LSA for its definition, typically based on multi-criteria decision analysis techniques [37] such as Analytical Hierarchy Process (AHP) [38,39], and Ordered Weighted Averaging (OWA) [20,31,40]. Here, we propose the qualitative GIS-OWA procedure adopted by Romano et al. [20] in the bioenergy context. The qualitative OWA approach, through the use of linguistic quantifiers [41], enables translation, in a simple way, of the decision-maker's preferences in multi-criteria decision analysis combination procedures [42].

The main inputs in qualitative GIS-OWA are criterion maps ($m$), criterion weights ($w_m$) and ordered weights ($v_m$), defining land use suitability as:

$$S_j = \sum_{m=1}^{n} v_m z_m \tag{10}$$

such that $S_j \in [0,1]$.

$v_m$ are defined as:

$$v_m = \left(\sum_{k=1}^{m} w_k\right)^{\alpha} - \left(\sum_{k=1}^{m-1} w_k\right)^{\alpha} \tag{11}$$

such that $v_m \in [0,1]$ and $\sum_{m=1}^{n} v_m = 1$, where:

$z_1 \geq z_2 \geq \ldots \geq z_n$ is the sequence obtained by reordering the value of standardized criterion maps $a_1, a_2, \ldots, a_n$;
$w_m$ is the criterion weight reordered according to the value of $z_m$;
$\alpha$ is the parameter associated with the RIM (Regular Increasing Monotone) linguistic quantifiers.

The criterion maps ($m$) represent crop-specific factors that contribute to the assessment of land suitability, including, among others, climate factors and soil conditions. It is important to point out that the type and number of factors to be considered depend on the specific context of the analysis. Due to variations in criteria scales, the fuzzy logic technique is proposed to standardize criterion maps within a suitability range [0,1] using appropriate membership functions [43,44], while the criterion weights are defined by AHP [38,39,45]. AHP is a widely used multi-criteria analysis approach in GIS environments, enabling users to establish factor weights through pairwise comparisons. These comparisons gauge the relative importance of criteria concerning suitability for the specified objective using Saaty's preference scale [45]. The selection of fuzzy functions and assignment of criterion weights depend on understanding the criterion–decision set relationship and available information to infer fuzzy membership and relative importance among all criteria. In Section 2.2, the criteria and their respective fuzzy functions and weights are presented for the case study.

Regarding the linguistic quantifier ($\alpha$ parameter), Romano et al. [20] argue that the success of crops in land use analysis relies on finding optimal agroecological conditions. Hence, incorporating numerous criteria enhances result reliability. In our case study, the "Almost all" quantifier ($\alpha$ = 10) best encapsulates this concept and contributes to order weight calculations. For further information about the qualitative GIS-OWA approach, see Romano et al. [20].

### *2.2. Case Study*

The Basilicata region (Southern Italy) chosen as the case study area (Figure 1) is a rural region with a typical Mediterranean climate. The AE-landUSE model was tested for rapeseed and cardoon as energy crops to be integrated into the current non-irrigated arable land (code 211 of Corine Land Cover map). Cardoon is a perennial plant adapted to the Mediterranean climate and identified by several authors as a possible energy crop [35], while rapeseed is an annual species that grows well in relatively high humidity and cooler temperatures, one widely cultivated for biodiesel production in Europe [7]. They were explicitly chosen for their different agroecological needs to test the model's utility.

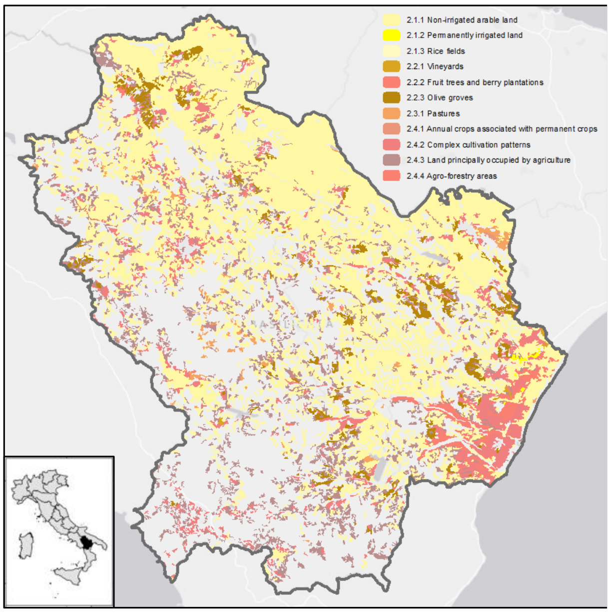



**Figure 1.** The Basilicata region (Southern Italy): agricultural land use (Corine Land Cover codes).

The analysis was carried out entirely in a GIS environment using QGIS software 3.16 [46] by creating georeferenced raster layers (100 m resolution) for each single factor (agroecological and economic) under investigation using Gauss Boaga East on Monte Mario Roma 1940 datum as the geographical reference system.

Economic data related to the cultivation costs and yield price were derived from Francaviglia et al. [47], considering conventional cultivation for rapeseed. Establishment costs (EUR), including crop management, materials and harvesting, are reported in Table 1.

**Table 1.** Cultivation costs for cardoon and rapeseed (EUR/ha) *.

| Costs | Cardoon | Rapeseed |
|---|---|---|
| Ploughing (45–50 cm) | 117 | 117 |
| Pulling up | 44 | |
| Harrowing | 48 | 48 |
| Fertilizer application (at sowing) | 24 | 24 |
| Nitrogen application (top dressing) | | 24 |
| Seeding | 40 | 40 |
| Rolling | | 35 |
| Herbicide spraying | | 32 |
| Threshing | | 109 |
| Crop residues chopping | | 41 |
| Certified seeds | 207 | 80 |
| Phosphoric fertilizer (300 kg $ha^{-1}$) | 132 | |
| NP fertilizer (at sowing) | | 120 |
| Nitrogen fertilizer (top dressing) | | 94 |
| Herbicides | | 39 |
| **Total establishment costs per ha** | **612** | **803** |
| ***Costs*** (***second year onwards***) | | |
| Nitrogen fertilizer | 24 | |
| Harvesting of total biomass | 210 | |
| Urea (150 kg $ha^{-1}$) | 68 | |
| **Total yearly costs per ha** | **302** | |

* Francaviglia et al. [47] (modified).

Considering low-input cultivation for sustainability reasons, optional agricultural operations proposed by the authors were not considered in the analysis. The yield price ($p$) was considered equal to 52 EUR/t for the cardoon above-ground biomass harvest to use for combustion and 468 EUR/t for the rapeseed grain harvest to use in biodiesel production. We considered a discount rate $r$ equal to 3.5% and a duration $n$ of the investment equal to 5 years. Cardoon is a perennial crop but, according to some authors, yields start to decrease after five years [48]. The latter was spatially estimated according to Equation (7), considering energy crop cultivation in rainfed conditions ($W_{used\,j}$ based on Equation (4)). The WUE was considered equal to 2.27 g/L of above-ground dry matter production [35] and 1.43 g/L of seed yield [49] for the cardoon and rapeseed, respectively. To define $S_j$, the crop-specific factors affecting the land use suitability (climatic and soil factors), the fuzzy functions used in the standardization procedure, the criterion weights and the ordered weights were derived from Viccaro et al. [15]. Detailed information is reported in Appendix A (Tables A2 and A3). It is important to note that data from the literature were chosen to test the model's validity; however, for site-specific analysis, more accurate data are recommended.

## 3. Results and Discussions

### *3.1. AE-landUSE Results*

Figure 2 shows the results of the land use suitability analysis for rapeseed (Figure 2a) and cardoon (Figure 2b). The suitability values range from 0.02 to 0.99 for rapeseed and from 0.53 to 0.97 for cardoon. On average, rapeseed shows lower suitability values compared to cardoon (0.26 vs. 0.87). Being a Mediterranean crop, cardoon can thrive with lower rainfall levels and in arid conditions [35,50], which makes it more suitable for cultivation on non-irrigated arable land in the Basilicata region, characterized by a typical Mediterranean climate. For a better interpretation of the results and to better describe the potential expansion of energy crops in the region, the suitability maps were reclassified according to the FAO suitability classes: not suitable (N), marginally suitable (S3), moderately suitable (S2) and highly suitable (S1) (Figure 2c,d). The range of suitability values for each class was defined according to the method of [51] as follows: not suitable (N, $S_j \leq 0.13$), marginally suitable (S3, $0.14 \leq S_j \leq 0.48$), moderately suitable (S2, $0.48 < S_j \leq 0.80$) and highly suitable (S1, $S_j > 0.80$).

As can be seen in Figure 2c,d, non-irrigated arable land predominantly falls into classes S3 (marginally suitable) and NS (not suitable) for rapeseed and into class S1 (highly suitable) for cardoon. Considering rapeseed, out of 380,350 ha of non-irrigated arable land, approximately 76% were classified as marginally suitable (S3) (287,814 ha), and about 16% as not suitable (NS) (59,188 ha). Only 7% and 1% were classified as moderately suitable (S2) (27,786 ha) and highly suitable (S1) (5562 ha), respectively. In contrast, about 10% of non-irrigated arable land was classified as moderately suitable (S2) (39,425 ha) and 90% as highly suitable (S1) (340,925 ha) for cardoon. Neither the not suitable (NS) nor the marginally suitable (S3) classes were present in the region.

In such a context, defining the region's potential in terms of land that could be dedicated to energy crop cultivation becomes quite challenging. Of course, as done in previous studies, we could have limited the choice to land showing high suitability due to lower economic risk. However, the main questions were (i) which energy crop to choose when land is classified as highly suitable for all energy crops, as observed in our study in the southern part of the region, and (ii) whether it is correct to exclude land showing moderate suitability even though there are potential economic risks. From the farmers' point of view, the choice is based on the economic return, especially when selecting among alternatives. The main factor influencing the spatial variability of the economic outcomes is, of course, the crop yields. Figure 3 shows the yields for rapeseed (Figure 3a) and cardoon (Figure 3b), expressed in tons of grain and dry above-ground biomass per ha, respectively. On average, the rapeseed yield is about 0.48 t/ha, with a minimum of 0.02 and a maximum of 3.47 t/ha, while the cardoon yield is 8.11 t/ha, with a minimum of 2.54 t/ha and a maximum of 17.82 t/ha. The lower yields are recorded in the northeast part of the region, characterized by lower rainfall compared to the southern part, where higher yields are recorded. The spatial variability in production significantly influences the economic outcomes, as illustrated in Figure 4.

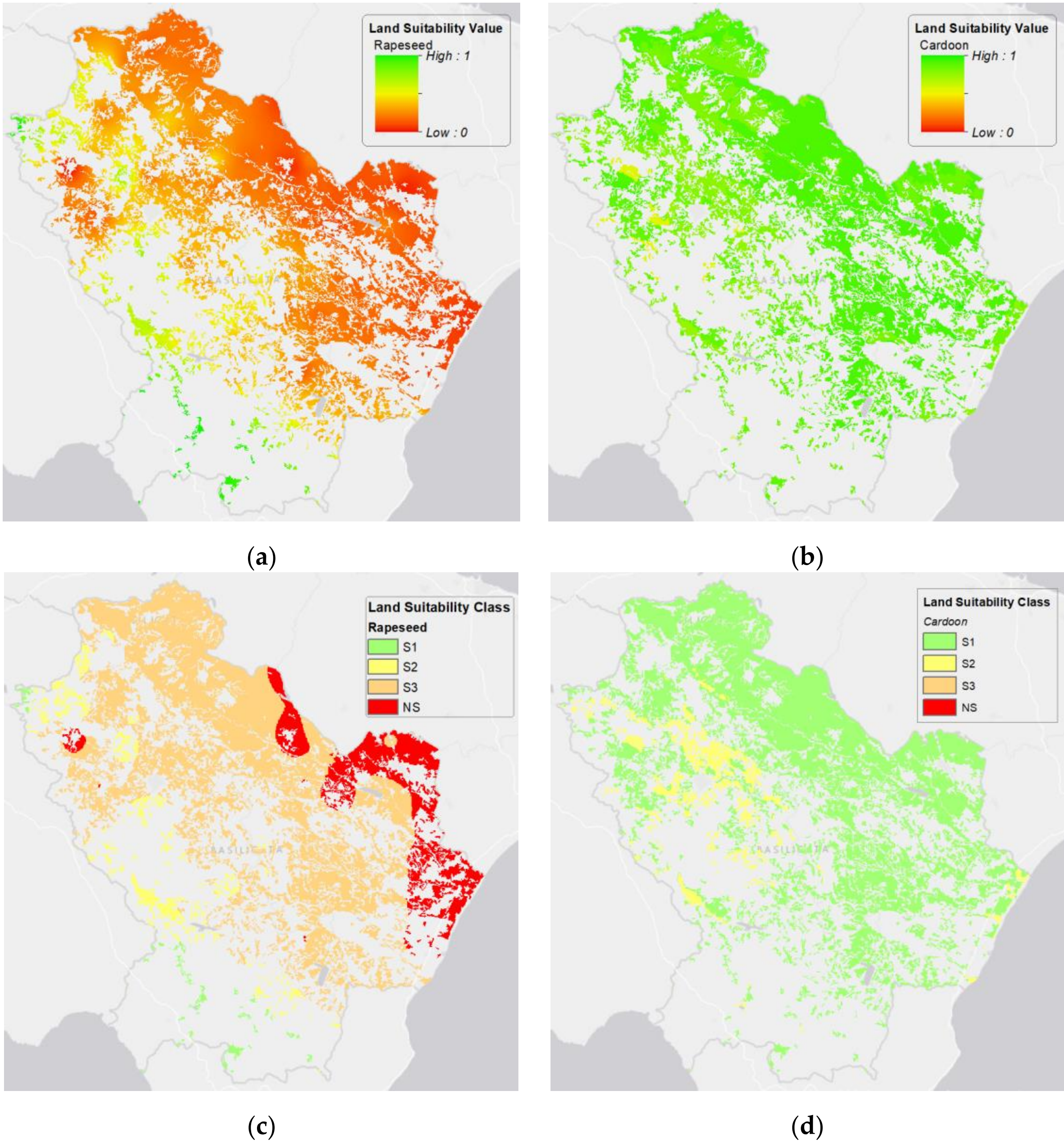
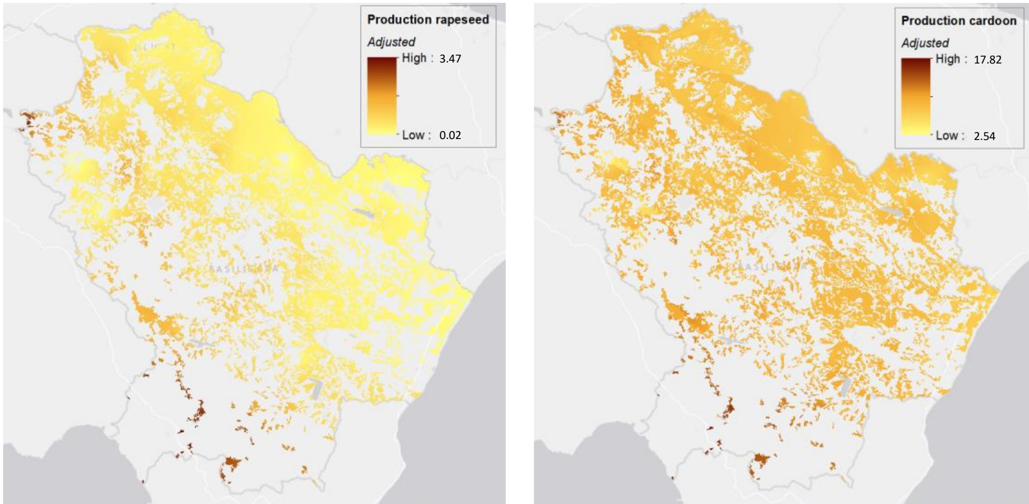


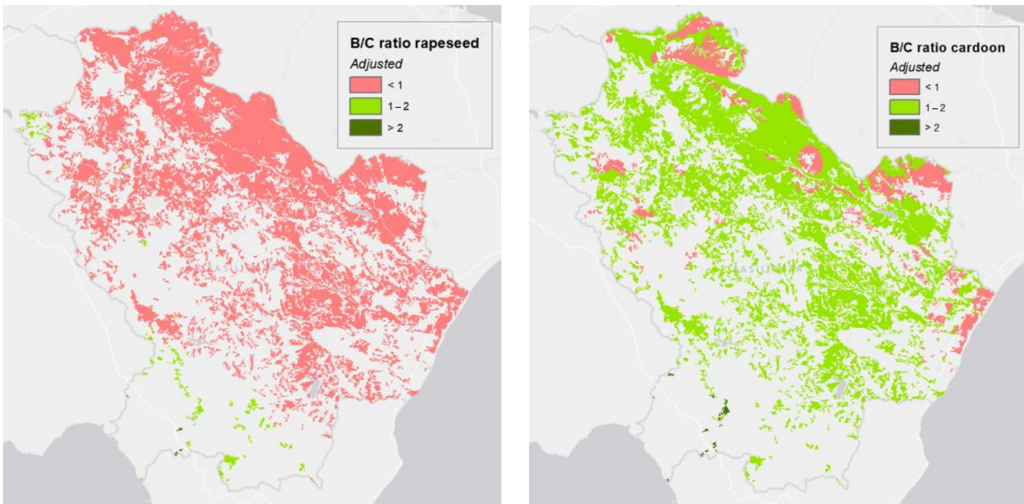

**Figure 2.** The figures show the results of the land suitability analysis. (**a**) Map of land suitability values for rapeseed; (**b**) map of land suitability values for cardoon; (**c**) map of land suitability classes for rapeseed; (**d**) map of land suitability classes for cardoon. (Note: not suitable (NS), marginally suitable (S3), moderately suitable (S2) and highly suitable (S1); see Table A1).

Figure 4 depicts the results of the AE-landUSE model, where the cost-effectiveness of energy crop cultivation is verified with $B/C_j > 1$, indicating that benefits outweigh costs; conversely, $B/C_j < 1$ indicates that costs exceed benefits, suggesting that the investment may not be financially feasible or economically justified. As can be seen, the results differ in part from those obtained with the land suitability analysis. Only a portion of the land showing high suitability for cardoon also demonstrates economic feasibility. More specifically, out of 340,925 ha with high suitability, 291,746 ha (about 86%) show a $B/C_j > 1$ (Table 2). These results are crucial for accurately assessing the region's energy crop potential. Considering all highly suitable land, we would have risked including land where farmers might have experienced a negative economic return. Simultaneously, we would have underestimated the potential by prematurely excluding areas classified as moderately suitable. In fact, upon closer examination of the results, approximately 82% (32,318 ha) of land classified as moderately suitable could also be dedicated to cardoon cultivation, as the benefit–cost ratio is higher than 1. Consequently, it can be concluded that about 85% (324,064 ha) of non-irrigated arable land in the region can be dedicated to cardoon cultivation. The results for rapeseed are quite similar: 100% of the highly suitable land shows a $B/C_j > 1$, while only 7% of the land classified as moderately suitable, resulting in a rapeseed cultivation potential of 7546 ha.




(**a**) (**b**)

**Figure 3.** Maps of energy crops' yields. (**a**) Tons of rapeseed grain per ha; (**b**) tons of cardoon dry above-ground biomass per ha.




(**a**) (**b**)

**Figure 4.** Maps of benefit–cost ratio for rapeseed (**a**) and cardoon (**b**).

The AE-landUSE model also enables us to compare alternatives. In the southern part of the region, where economic feasibility is achieved for both cardoon and rapeseed, it is possible to choose the best alternative, namely, the one with a higher benefit–cost ratio. In our case, cardoon is preferred since it shows a $B/C_j > 2$.

As mentioned by different authors, economic aspects should not be neglected in the land–water–energy–food nexus for holistic and well-managed utilization of resources in energy crop cultivation [9,15]. We can assert that economic feasibility should be the starting point to assess the land–water–energy nexus. Farmers must allocate resources and effort only in areas where energy crop cultivation results in positive economic outcomes. By incorporating the land suitability analysis into the model, AE-landUSE helps identify areas where the economic feasibility of energy crop cultivation is achieved by focusing on a single indicator, thus facilitating the decision-making process as a basis for more in-depth analysis of land, water and energy resources.

**Table 2.** Land distribution (ha) among land suitability class considering land suitability values and benefit–cost ratio values for rapeseed and cardoon.

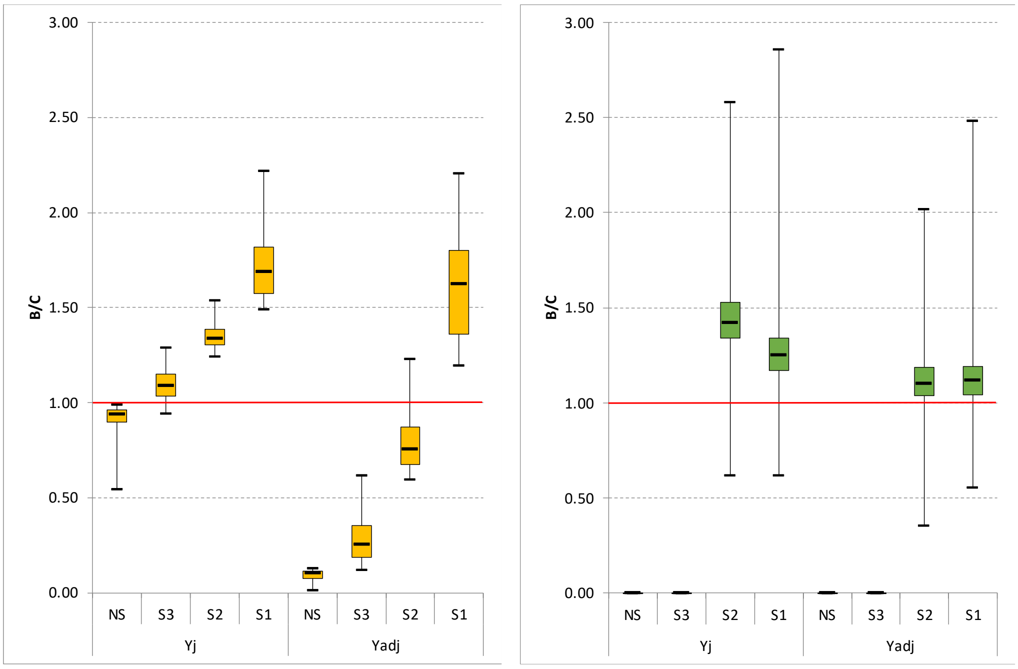
| Energy Crops | NS | S3 | S2 | S1 | Total |
|---|---|---|---|---|---|
| Rapeseed | | | | | |
| Land per suitability class (ha) | 59,188 | 287,814 | 27,786 | 5562 | 380,350 |
| Land with B/C > 1 (ha) | 0 | 0 | 1984 | 5562 | 7546 |
| Cardoon | | | | | |
| Land per suitability class (ha) | 0 | 0 | 39,425 | 340,925 | 380,350 |
| Land with B/C > 1 (ha) | 0 | 0 | 32,318 | 291,746 | 324,064 |

### 3.2. Sensitivity Analysis

The sensitivity analysis compared the results of the AE-landUSE model, where energy crop yields are calculated according to Equation (7) ($Y_{adj_j}$ scenario), with the results obtained by calculating yields according to Equation (3) ($Y_j$ scenario), namely, without considering the land suitability results in the estimation. Figure 5 shows the distribution of the benefit–cost ratio recorded in the four land suitability classes for both the $Y_j$ and $Y_{adj_j}$ scenarios, while Table 3 presents the results in terms of land potential. As can be seen, the distributions differ significantly among scenarios for both energy crops under analysis. In the case of rapeseed, in the $Y_j$ scenario, the benefit–cost ratio is higher than 1 for all land in the S2 suitability class and also for most of the land in the S3 suitability class, resulting in different outcomes compared to the $Y_{adj_j}$ scenario in terms of land potential. In this case, out of 380,350 ha of non-irrigated arable land, 297,960 ha can be dedicated to rapeseed cultivation, approximately 78% of the total compared to 2% in the $Y_{adj_j}$ scenario. Similar results are observed for cardoon: in the $Y_j$ scenario, most of the moderately suitable land (S2) shows a higher benefit–cost ratio compared to those recorded in the $Y_{adj_j}$ scenario. In this case, the potential for cardoon cultivation in the $Y_j$ scenario is equal to 375,129 ha, about 99% of the total compared to 85% in the $Y_{adj_j}$ scenario. Not considering land suitability analysis in calculating the benefit–cost ratio can lead to overestimating the region's potential, resulting in high economic risk in areas with lower suitability levels.

**Table 3.** Land distribution (ha) among land suitability classes considering land suitability values and benefit–cost ratio values for rapeseed and cardoon ($Y_j$ and $Y_{adj_j}$ scenarios).

| | Energy Crops | NS | S3 | S2 | S1 | Total |
|---|---|---|---|---|---|---|
| | Rapeseed | | | | | |
| | Land (ha) | 59,188 | 287,814 | 27,786 | 5562 | 380,350 |
| $Y_{adj_j}$ | Land with B/C > 1 (ha) | 0 | 0 | 1984 | 5562 | 7546 |
| $Y_j$ | Land with B/C > 1 (ha) | 0 | 264,685 | 27,786 | 5562 | 297,960 |
| | Cardoon | | | | | |
| | Land (ha) | 0 | 0 | 39,425 | 340,925 | 380,350 |
| $Y_{adj_j}$ | Land with B/C > 1 (ha) | 0 | 0 | 32,318 | 291,746 | 324,064 |
| $Y_j$ | Land with B/C > 1 (ha) | 0 | 0 | 39,180 | 335,948 | 375,129 |




(**a**) (**b**)

**Figure 5.** Benefit–cost ratio value distribution in the land suitability class both in the $Y_j$ and $Y_{adj_j}$ scenarios for rapeseed (yellow box-plot) (**a**) and cardoon (green box-plot) (**b**).

## 4. Conclusions

Bioenergy will play a key role in limiting global warming and achieving sustainable development goals, as recognized by initiatives such as the IEA roadmap "Net Zero by 2050" and the European Union's renewable energy targets. In this context, the cultivation of dedicated energy crops emerges as a crucial strategy, prompting researchers to explore methodologies for integrating energy crops into agricultural systems sustainably. This paper discusses the growing popularity of land suitability analysis within geographic information systems (GIS-LSA) for identifying suitable locations for energy crops. However, it also recognizes the need for a comprehensive approach that considers broader sustainability aspects related to land management, especially in terms of economic feasibility. Farmers are willing to cultivate energy crops in the current agricultural system only with positive economic return.

Based on that, this paper proposes an innovative model called AE-landUSE, which integrates cost–benefit analysis (CBA) and land use suitability analysis within GISs. By considering both agroecological and economic criteria, the model aims to identify areas where energy crop cultivation is environmentally and economically feasible. This study applies the AE-landUSE model to the Basilicata region in Southern Italy, focusing on rapeseed and cardoon as potential energy crops by adopting data input from the literature. The results demonstrate the spatial variability in land suitability and economic feasibility, highlighting the importance of considering both factors in decision-making. Furthermore, this paper discusses a sensitivity analysis which compared the results of the AE-landUSE model with and without considering land suitability. The analysis revealed significant differences in the potential for energy crop cultivation, underscoring the importance of incorporating land suitability into economic assessments to avoid overestimation and mitigate financial risks.

Overall, this paper provides valuable insights into integrating bioenergy into agricultural systems, emphasizing the need for a holistic approach that balances environmental sustainability with economic viability. In site-specific analysis, more accurate data inputs are recommended. The proposed AE-landUSE model represents a promising tool for guiding decision-makers in allocating resources effectively and promoting sustainable energy crop cultivation.

**Author Contributions:** Conceptualization, M.V., S.R. and M.C.; methodology, M.V.; formal analysis, I.R.; data curation, I.R.; writing—original draft preparation, M.V.; writing—review and editing, M.V., S.R., I.R. and M.C.; visualization, M.C.; project administration, M.C. and S.R.; funding acquisition, M.C. and S.R. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was funded by the Next Generation EU—Italian NRRP, Mission 4, Component 2, Investment 1.5, call for the creation and strengthening of 'Innovation Ecosystems', building 'Territorial R&D Leaders' (Directorial Decree n. 2021/3277)—project Tech4You—Technologies for climate change adaptation and quality of life improvement, n. ECS0000009. This work reflects only the authors' views and opinions, and neither the Ministry for University and Research nor the European Commission can be considered responsible for them.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Conflicts of Interest:** The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

## Appendix A

**Table A1.** Land suitability classes according to the FAO [21], as cited in [52].

| Suitability Classes | Description |
|---|---|
| S1, Highly suitable | Land having no significant limitations to sustained application for a given land use or only minor limitations. Nil to minor negative economic, environmental, health, and/or social outcomes. |
| S2, Moderately suitable | Land having limitations which in aggregate are moderately severe for sustained application of a given land use. Appreciably inferior to S1 land. Potential negative economic, environmental, health, and/or social outcomes if not adequately managed. |
| S3, Marginally suitable | Land having limitations which in aggregate are severe for sustained application of a given use. Moderate to high risk of negative economic, environmental, health, and/or social outcomes if not adequately managed. |
| N1, Not suitable | Land having limitations, which may be insurmountable. Limitations are so severe as to preclude successful sustained use of the land. Very high risk of negative economic, environmental, and/or social outcomes if not managed. |
| N2, Not suitable | Land having limitations, which appear so severe as to preclude any possibilities of successful sustained use of the land in the given manner. Almost certain risk of significant negative economic, environmental, and/or social outcomes. |

**Table A2.** Criterion maps, fuzzy function, and criterion and ordered weights for land use suitability of rapeseed [15].

| Criterion Maps | Fuzzy Function | Criterion Value | Fuzzy Value | Criterion Weights | Ordered Weights |
|---|---|---|---|---|---|
| Crop-specific thermal index | Null * | - | - | 0.292 | 0.0315 |
| Seasonal rainfall deficit (mm) | Decreasing sigmoidal | 0 | 1.00 | 0.292 | 0.9684 |
| | | 50 | 0.00 | | |

**Table A2.** *Cont.*

| Criterion Maps | Fuzzy Function | Criterion Value | Fuzzy Value | Criterion Weights | Ordered Weights |
|---|---|---|---|---|---|
| Carbonates (% $CaCO_3$) | User defined | <0.5 | 1.00 | 0.024 | 0.0000 |
| | | 0.5–1 | 1.00 | | |
| | | 1–5 | 1.00 | | |
| | | 5–10 | 1.00 | | |
| | | 10–25 | 1.00 | | |
| | | 25–40 | 0.93 | | |
| | | >40 | 0.84 | | |
| Soil depth (cm) | User defined | <25 | 0.58 | 0.073 | 0.0000 |
| | | 25–50 | 0.70 | | |
| | | 50–100 | 0.90 | | |
| | | 100–150 | 1.00 | | |
| | | >150 | 1.00 | | |
| Gravel (%) | User defined | 0 | 1.00 | 0.039 | 0.0000 |
| | | 1–5 | 0.90 | | |
| | | 5–15 | 0.85 | | |
| | | 15–35 | 0.65 | | |
| | | 35–70 | 0.50 | | |
| | | >70 | 0.20 | | |
| Soil reaction (pH) | User defined | <4.5 | 0.75 | 0.024 | 0.0000 |
| | | 4.5–5.5 | 0.85 | | |
| | | 5.6–6.5 | 0.92 | | |
| | | 6.6–7.3 | 1.00 | | |
| | | 7.4–7.8 | 0.95 | | |
| | | 7.9–8.4 | 0.95 | | |
| | | 8.5–9.0 | 0.90 | | |
| Soil texture | User defined | Coarse | 0.65 | 0.128 | 0.0000 |
| | | Moderately coarse | 0.88 | | |
| | | Medium | 0.88 | | |
| | | Moderately fine | 0.95 | | |
| | | Fine | 0.91 | | |
| Drainage | User defined | Rapid | 0.70 | 0.128 | 0.0002 |
| | | Good | 0.93 | | |
| | | Mediocre | 0.80 | | |
| | | Slow | 0.70 | | |
| | | Very slow | 0.50 | | |
| | | Prevented | 0.30 | | |

* CTI (crop-specific thermal index) range is between 0 and 1 so it is not necessary to standardize it.

**Table A3.** Criterion maps, fuzzy function, and criterion and ordered weights for land use suitability of cardoon [15].

| Criterion Maps | Fuzzy Function | Criterion Value | Fuzzy Value | Criterion Weights | Ordered Weights |
|---|---|---|---|---|---|
| Crop-specific thermal index | Null * | - | - | 0.289 | 0.1624 |
| Annual rainfall (mm) | Increasing sigmoidal | 450 | 0.00 | 0.289 | 0.0000 |
| | | 1000 | 1.00 | | |

**Table A3.** *Cont.*

| Criterion Maps | Fuzzy Function | Criterion Value | Fuzzy Value | Criterion Weights | Ordered Weights |
|---|---|---|---|---|---|
| Carbonates (% $CaCO_3$) | User defined | <0.5 | 1.00 | 0.023 | 0.0000 |
| | | 0.5–1 | 1.00 | | |
| | | 1–5 | 1.00 | | |
| | | 5–10 | 1.00 | | |
| | | 10–25 | 1.00 | | |
| | | 25–40 | 0.90 | | |
| | | >40 | 0.80 | | |
| Soil depth (cm) | User defined | <25 | 0.58 | 0.129 | 0.0003 |
| | | 25–50 | 0.70 | | |
| | | 50–100 | 0.90 | | |
| | | 100–150 | 1.00 | | |
| | | >150 | 1.00 | | |
| Gravel (%) | User defined | 0 | 1.00 | 0.039 | 0.0953 |
| | | 1–5 | 0.90 | | |
| | | 5–15 | 0.81 | | |
| | | 15–35 | 0.70 | | |
| | | 35–70 | 0.55 | | |
| | | >70 | 0.35 | | |
| Soil reaction (pH) | User defined | <4.5 | 0.80 | 0.023 | 0.0002 |
| | | 4.5–5.5 | 0.90 | | |
| | | 5.6–6.5 | 0.92 | | |
| | | 6.6–7.3 | 1.00 | | |
| | | 7.4–7.8 | 0.95 | | |
| | | 7.9–8.4 | 0.95 | | |
| | | 8.5–9.0 | 0.90 | | |
| Soil texture | User defined | Coarse | 0.70 | 0.085 | 0.0019 |
| | | Moderately coarse | 0.80 | | |
| | | Medium | 0.90 | | |
| | | Moderately fine | 1.00 | | |
| | | Fine | 0.95 | | |
| Drainage | User defined | Rapid | 0.70 | 0.126 | 0.7399 |
| | | Good | 0.90 | | |
| | | Mediocre | 0.80 | | |
| | | Slow | 0.70 | | |
| | | Very slow | 0.50 | | |
| | | Prevented | 0.30 | | |

* CTI (crop-specific thermal index) range is between 0 and 1 so it is not necessary to standardize it.

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