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Biomass Potential of the Marginal Land of the Polish Sudetes Mountain Range

Marek Helis [1], Maria Strzelczyk [1], Wojciech Golimowski [2,*], Aleksandra Steinhoff-Wrześniewska [1], Anna Paszkiewicz-Jasińska [1], Małgorzata Hawrot-Paw [3], Adam Koniuszy [3] and Marek Hryniewicz [1]

1 Institute of Technology and Life Sciences—National Research Institute Falenty, 3 Hrabska Avenue, 05-090 Raszyn, Poland; m.helis@itp.edu.pl (M.H.); m.strzelczyk@itp.edu.pl (M.S.); a.wrzesniewska@itp.edu.pl (A.S.-W.); a.paszkiewicz@itp.edu.pl (A.P.-J.); m.hryniewicz@itp.edu.pl (M.H.)
2 Department of Agroengineering and Quality Analysis, Faculty of Engineering and Economics, Wroclaw University of Economics and Business, Komandorska 180/120 Street, 53-345 Wroclaw, Poland
3 Department of Renewable Energy Engineering, West Pomeranian University of Technology in Szczecin, Papieza Pawla VI 1, 71-459 Szczecin, Poland; Malgorzata.Hawrot-Paw@zut.edu.pl (M.H.-P.); Adam.Koniuszy@zut.edu.pl (A.K.)
* Correspondence: wojciech.golimowski@ue.wroc.pl; Tel.: +48-71-368–0288

Abstract: Marginal land is the area remaining in agricultural use, which is not suitable for food production because of its unfavorable ecological, anthropological, and economic conditions. A certain amount of such land exists in mountainous areas. An analysis was undertaken on the example of the Polish Sudeten mountain range of energy use. The study aimed to estimate the biomass potential for the efficient use of agricultural land in mountain areas. The characteristics of the Polish Sudeten Mountains mountain range were characterized using Geographic Information System (GIS) methods. The Polish Sudeten Mountains covers an area of 370,392 ha, 95,341 ha of which is arable land, 35,726 ha of which is class 5 bonitation land with a northern exposure of 19,030 ha and southern exposure of 16,696 ha. Depending on the sowing structure, we can obtain 331,639 tons/year of dry biomass (*Miscanthus sacchariflorus* on the southern and *Helianthus tuberoses* on northern exposure). Fertilization levels will significantly affect low yielding plants, and water stress significantly reduced yields in all cases. Due to the steep slope of the 5th-grade halves and intensive rainfall in the mountain region, the establishment of perennial plantations is recommended. The research shows that after the first year of cultivation, yields of 9.27 tons/ha of dry matter can be obtained with a low yield of trees, shrubs and perennials.

Keywords: marginal land; biomass; energy crops; GIS; perennial planters

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1. Introduction

Marginal soils are defined as soils remaining in agricultural use or in the cultivated land register which, due to adverse natural, anthropogenic, and economic conditions [1], have low productivity or are unsuitable for healthy food production [2,3]. Growing biomass for energy on agricultural land suitable for food production has been criticized [4]. It has been noted that, unlike fertile agricultural land, marginal land is underutilized due to lack of food production opportunities on it and political considerations [5,6]. Designing marginal areas for functions other than food production should lead to changes in their possible development, taking into account social, economic, and environmental aspects [7]. It has been unequivocally stated that biomass production for energy purposes is an excellent way to manage them [8].

The problem of identifying and managing marginal land is the subject of many studies [9]. Due to the large population, biomass production for energy purposes is performed on marginal land in China. An example is mulberry plantations, which are cultivated for biomass after fruit production [10]. The possibility of growing a selective

variety of sorghum for ethanol production in Inner Mongolia was also studied. The study shows that despite the lower sugar content of the plants, it is a good direction for development [11]. Following a policy on bioenergy development in the UK, introducing energy crops on marginal lands such as miscanthus or willow was proposed. Farmers did not support the Policy Initiative because of the need to change production profiles and the lack of guarantees for the profitability of crops [12]. The possibility of producing four fast-growing crops for nine years over 3-year rotation cycles in marginal land in the Mediterranean was studied. Willow, poplar, and black locust energy crops produced 12, 9, and 7 tons of dry mass per ha per year. It was a good result considering that these are poor lands [13]. The suitability of marginal land in the Upper Mississippi River Basin (UMRB) was assessed. It was found that 60% of the area was suitable for growing bio feedstock crops [14]. The 4-year average yield of 12 miscanthus species in the Yellow River Delta was limited due to climatic factors, ranging from 2 to 32 tons/ha [15]. The results of large plantations of jatropha, a plant with low water availability requirements, indicate a significant impact of climate change causing plant stress. As a consequence, many large plantations in Ethiopia have collapsed [16]. Studies done in Germany indicate the low profitability of biomass production on marginal land. This was due to the low yield of willow, high harvesting and transport costs, and low biomass purchase prices [17]. Similar to Germany, in Sweden, biomass production on marginal land is unprofitable. When subsidies are taken into account, profitability improves but is still lower than fallow land [18]. Studies performed in Portugal indicate that performing controlled cultivation on marginal land has a more positive effect on inhibiting soil erosion than afforestation [19]. Furthermore, it was found that replacing maize and soybean crops with herbaceous grasses and miscanthus significantly improved water quality as a result of reduced soil erosion [20]. The yield of grass cultivation in Ireland on marginal land was more or less 15% lower than on agriculturally used land on the island. The potential for biomass production on Ireland's marginal land would cover the requirements of biofuel production [21].

It is estimated that on the territory of Poland, 12% of agricultural land (over 2 million ha) is marginal land. Obtaining satisfactory and economically viable biomass yields requires the application of appropriate agrotechnical treatments, including fertilization and protection against pests [22]. In 2010, the surface area taken by energy crops in Poland was 154.100 ha, which accounted for 0.9% of the total agricultural land. The structure of energy crops is dominated by energy trees and shrubs; on forest land their share accounted for 88.9%. The share of energy crops on arable land accounted for 11.1% [23]. One of the technological directions of biomass use in Poland is the production of ethanol as a biofuel. Research shows that the cultivation of grasses and sorghum can be economically justified [24,25]. In Poland, biomass potential was measured using GIS methods in two provinces. The authors emphasize that the maps are a useful tool for optimizing investments in biomass-based power plants in the future [26,27].

Biomass production occurs in plantations of woody, shrubby, tuberous, or grassy plants with high annual biomass growth and moderate soil requirements [28]. For biomass production, woody plants: poplar (*Populus* sp.) [29] (*Robinia pseudoacacia* L.) [30], shrubby plants: willow (*Salix* sp.) [31], perennial plants: sunflower (*Helianthus* sp.) [32], especially tuberous sunflower (*Helianthus tuberosus* L.) [33], and grasses: (*Spartina pectinate Bosc ex Link*) [34], miscanthus [24] incredibly giant miscanthus (*Miscanthus x giganteus* J.M Greef and Deuter ex Hodk. and Renvoize) [35].

The study aimed to determine the production potential of lignocellulosic biomass using a multi-parametric regional spatial analysis. The analysis was based on the results of pot experiments. The adopted method made it possible to experiment on many species in diversified yield and utilization groups. This made it possible to simulate water stress under different fertilizer conditions. The results of the vascular study gave the possibility to estimate the single biomass production potential in selected areas. The analysis was performed in marginal mountain areas due to more marginal features than in lowland areas. The Sudeten range was selected for analysis because it is one of the largest in Poland.

For example, a mountain area was selected for the study. The analysis was carried out using the GIS method, which allows for the possibility of transforming algorithms to tally the attributes of cartographic layers.

2. Materials and Methods

2.1. Pot Experiments

The experiment was conducted under controlled conditions in a vegetation hall at the Research Station of the Institute of Technology and Life Sciences—National Research Institute. The plants were grown in large vases with a capacity of 18 L. The vases were filled with slightly loamy sand collected from the top arable layer of the field. The soil is classified as weak soil type from soil of V quality class [36]. This soil is not very fertile in agricultural terms. In order to determine the effect of water and nutrient stress on yield, two variable factors were used in the experiment: the level of mineral fertilization and the amount of water. These are the main factors determining the yield of plants both in terms of their quantity and quality. In all plant species, three different levels of fertilization and three different levels of irrigation were applied. When irrigating plants, the W 100 variant corresponded to the amount of dose to the state of achieving PPW (Field Water Capacity —the maximum amount of water that the soil is able to hold by attraction forces occurring on the surface of soil particles without gravitational leaching). In subsequent variants, the water application rate was reduced by approximately 15% (variant W 85) and 30% (variant W 70). Water application in summer was 2–3 times per week, while outside the summer period, it was one time. In the case of reduced doses, in the period of hot weather accompanied by very high evapotranspiration, a need arose to make additional emergency irrigations, maintaining the principle of applying the same dose within the variant. Tap water was used for irrigation. The matrix of the experiment is shown in Table 1, taking as independent variables the type of plant and fertilization and irrigation. The determining variables were adopted quantitative, i.e., the yield expressed as dry weight of biomass from the vase.

Table 1. Matrix of the pot experiment.

Type Plant	Plant Species	Symbol	NPKI	W 100	W 85	W 70
			N:P:K kg/ha	dm^3/pot/year		
Woody plants	Populus nigra	PN	NPK I 45:15:30	540	485	414
	Salix purpurea	SP		537	484	418
	Salix viminalis	SV		519	461	406
	Robinia pseudoacacia	RP		555	493	423
Grasses plants	Spartina pactinata	SPP	NPK II 90:30:60	513	461	399
	Miscanthus sacchariflorus	MSA		516	465	406
	Miscanthus giganteus	MG		520	466	400
	Miscanthus sinensis	MSI		512	459	406
Perennial plants	Helianthus salicifolius	HS	NPK III 135:45:90	527	456	411
	Silphium perfoliatum	SPE		558	506	440
	Helianthus tuberosus	HT		632	538	502

Each variant of the pot experiment was performed in three repetitions to verify the results' repeatability. Averaged values used in further calculations. Plants in the vase after the vegetation period were cut, weighed, crushed, and dried.

2.2. GIS-Based Estimation of Marginal Land

One of the basic data for estimating the potential of agricultural crops is the area of crops of the studied region. Research conducted on large areas with heterogeneous structures requires the use of cartographic maps. One of the applied research tools is Geographic Information Systems (GIS), commonly used in this kind of research [37].

At the initial stage of preparation of thematic maps, the cartographic works were developed (height and slope of the terrain, soil species in the first depth level, soil agricultural usefulness complex, soil contamination with heavy metals and sulfur, boundaries of protected nature areas). They were selected and exported from the existing base to separate files of the GIS system and then limited into compartments required in the erosion soil model.

The cartographic resources of types, kinds, and species of soils and agricultural usefulness complexes existing in the Institute of Soil Science and Technology (compiled from analog maps on the scale 1:5000) were used. Slope gradients, elevation intervals, and slope exposures were obtained after transformation of the 2013 airborne laser scanning (LIDAR) elevation data recorded according to standard 1.2 published by ASPRS (American Society for Photogrammetry and Remote Sensing). The map of soil contamination with selected heavy metals and sulfur was obtained due to vectorization of analog maps of contamination with these elements obtained from published resources of the Lower Silesian Department of Geodesy and Cartography.

The next stage was the transformation of selected attributes of cartographic layers according to the model algorithm. In this study, two types of marginal soils were distinguished: marginal soils of erosion and contaminated type. Other types of marginal soils described in the literature were not taken into account due to their small share in the total area of the Polish Sudeten Mts.

The occurrence of marginal erosive soils depends mainly on the slope of the terrain. It concerns rendsina, loess, and sand soils primarily already at slopes higher than 6 degrees and in the case of clay and loam soils at slopes higher than 10 degrees. These areas are highly vulnerable to erosion and are classified as alternatively marginal. Alternatively marginal soils refer to arable land which can be cultivated in cases of regional conditions or general economic prosperity subject to ecological or weather restrictions. On the other hand, all soils with a slope of more than 15 degrees belong to the proper marginal soils, i.e., land which should be excluded from intensive use or planned for cultivation to counteract soil erosion.

In the case of contaminated marginal soils, their classification depends on the degree of contamination of soils with heavy metals and sulfur and the agricultural usefulness complex of the soils. In the Polish Sudeten Mountains, there are areas of soil contamination with heavy metals and sulfur to a medium and high degree, which is mainly connected with the former activity of industrial plants.

In this study, a model of marginal soils was used using spatial data on natural factors in a mountainous area, which is consistent with assumptions made in other studies [19,38,39]. Natural data, mainly related to soil fertility and terrain relief, were also associated in the context of energy obtained from biomass [40].

3. Results and Discussion

These plants can be divided into three main groups: trees and shrubs, grasses, and perennials. They are characterized by good tolerance to changing climatic conditions. Many of the perennial arable crops (PAC) species are characterized by low habitat and soil requirements, so the possibility of their cultivation on marginal lands is considered. These lands do not compete with the food sector and do not disturb the proper functioning of forest management [41].

The water needs of plants are generally defined by the height of their yield at optimal water supply and given in millimeters [42]. The height of these needs depends, among others, on the plant species, amount and distribution of precipitation. Most species of fast-growing plants, to which perennial industrial plants belong, are characterized by high demand for water, especially in the first year of cultivation. Thus, precipitation and water availability to plants is the main factor limiting their yield.

Water losses, on the other hand, are related to plant transpiration and evaporation, referred to by one term—evapotranspiration. Evapotranspiration is one of the main components of water balance. The literature distinguishes two types of evapotranspiration, namely potential and actual evapotranspiration [43]. Potential evapotranspiration is most often determined because, according to Bogawski [44], the calculation of actual evapotranspiration is very difficult. The amount of potential evapotranspiration is a variable quantity, depending on climatic factors, including air temperature [45].

4. Results of Pot Tests on Trees and Shrubs

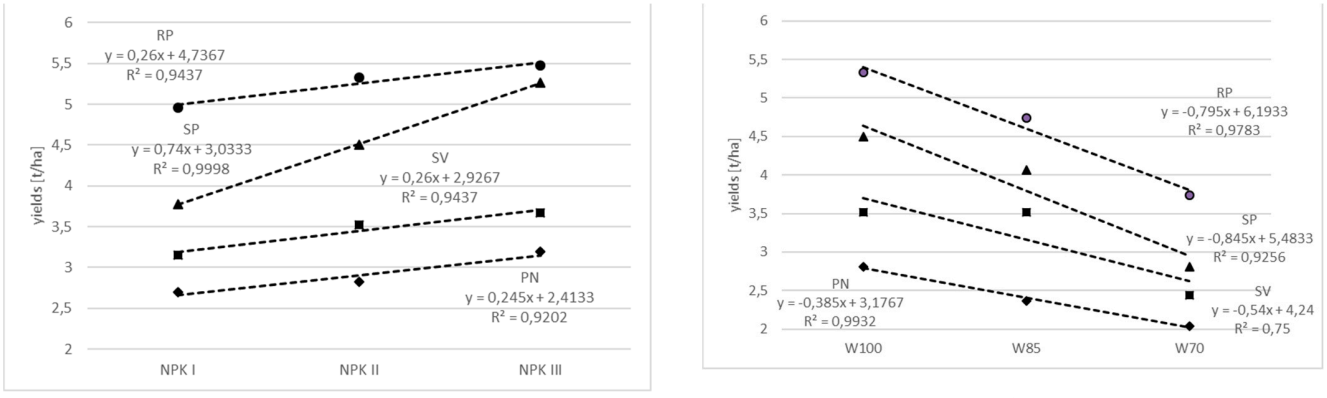
The average annual temperature during the vegetation period of plants was 17.4 °C. The highest temperatures averaging 20 °C were recorded from June to August. The pH of the soil is significant in the availability of phosphorus and potassium and consequently in the drought resistance of plants [46]. In the pot experiments, the soil reaction was acidic and slightly acidic, mean pH of 6.3 ± 0.2. It cannot be indicated that the combinations used in the pot experiments (water and fertilizer) significantly affected the reaction of the soils analyzed.

Our study shows that water stress has a significant effect on the yield of trees and shrubs in the first year of vegetation. The change of dosage in relation to the reference sample by 15 and 30% resulted in a decrease in yielding by 0.39 t/ha dry matter for PN to even 0.84 t/ha dry matter for SP, respectively (Table 2). In the studied region of the Polish Sudeten mountain range. Over the last 15 years, no level of precipitation below the adopted reference dose has been recorded, while the obtained results of the study allow simulating cultivation in other areas where lower precipitation is recorded. The supply of nutrients to the soil has a significant effect on plant yield in all the cases studied. The NPK II fertilization level depleted by 50% and enriched to 150% of the reference dose was taken as the reference trial. Own research showed that an increase of nutrients N every 45 kg/ha, P 15 kg/ha, K 30 kg/ha caused a significant increase of 0.75 t/ha of dry matter in the case of SP. In other cases, this increase was less significant, 0.26 and 0.25 t/ha dry matter, respectively (Table 2).

Table 2. Dependence of dry matter on fertilization and soil irrigation tree and shrub yields.

Plant Species	Dry Mass of the Sample (t/ha)					
	NPK I	NPK II	NPK III	W 100	W 85	W 70
PN	2.70 ± 0.46	2.82 ± 0.05	3.19 ± 0.26	2.81 ± 0.05	2.37 ± 0.23	2.04 ± 0.36
SP	3.78 ± 0.24	4.50 ± 0.32	5.26 ± 0.23	4.50 ± 0.32	4.07 ± 0.34	2.81 ± 0.10
SV	3.15 ± 0.18	3.52 ± 0.21	3.67 ± 0.18	3.52 ± 0.47	3.26 ± 0.47	2.44 ± 0.16
RP	4.96 ± 1.42	5.33 ± 0.64	5.48 ± 0.64	5.33 ± 0.64	4.74 ± 0.95	3.74 ± 0.21

The distribution of the mean values of the measurement points for almost all cases is linear, with a degree of fit of the normal distribution function at R2 > 0.92 (Figure 1). Energetic woody and shrub plants respond more strongly to water stress than to fertilizer dose. In this case, the reference trial was W 100 followed by water stress in 15% increments. Reducing irrigation levels results in a significant change in yield levels. For RP and SP, it is about 0.05 t/ha per 1% loss with respect to average rainfall levels. SV and PN were more resistant to the change in irrigation, a yield reduction of about 0.03 t/ha dry matter per 1% reduction in irrigation.



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

Figure 1. Change in yield of trees and shrubs in relation to (**a**) fertilization and (**b**) hydration.

In our own research, yields obtained with the application of a total water dose below 500 mm in all research series resulted in lower yields. In studies conducted in the south-western part of Poland, considerably lower yields of shrub willow were obtained in the Lower Silesian Lowlands [47] than in studies conducted in the Sudetenland sub-mountain region, characterized by the occurrence of a higher sum of precipitation compared with the lowland areas of the Lower Silesia. With short harvest cycles, yields of willow dry matter depend to a large extent on harvest frequency and the selection of a suitable cultivar, clone or hybrid [47–50]. The results obtained by Nowak et al. [47] under the conditions of Lower Silesia, dry matter yields of wicker willow harvested every year were much lower than those of willow harvested every two years and were, respectively, 5.6–9.4 and 13.1–20.6 t/ha depending on the clone grown. Water stress related to decreasing the amount of water does, in own research on individual variants, affect the decrease of dry matter yield of willow wicker. Jurczuk et al. [51] report that the yield of this species in the case of water shortage, without irrigation, ranged from 6 to 8 t/ha. Water shortage caused by drought may contribute to the loss of a plantation in the first year after its establishment, and on perennial plantations to a decrease in yield even up to 50% [52,53].

A slightly higher yield of dry biomass of Robinia acacia was obtained by [54]—11.7 t/ha per year, after the second and third years of cultivation, and 5.4 t/ha after the fourth year, whereas yields of dry biomass of Robinia on plantations in Hungary and the USA ranged from 5.7 to 14 t/ha per year. Stolarski et al. [28] in a three-year experiment conducted in the north-eastern part of Poland obtained Robinia acacia yields of 3.3 t/ha and the highest dry biomass yield was 4.4 t/ha per year. In our study, the highest yield of dry matter of 5.3 t/ha was obtained with a total water quantity above 500 mm (555 mm).

From pot experiments, perennial plants showed a strong response to both fertilization level and water stress. For HT and HS, nutrient deficiency, as well as nutrient excess, resulted in a significant yield decrease. Yield differences compared to the control crop were −20% to even −55%. Water stress for HT and HS with a 15% reduction in water dose resulted in a lower yield of more than −50%. The smallest changes were recorded when fertilization was changed at SPE from −6% to −21% while no significant change in yield was recorded at a reduced water rate (Table 3 and Figure 2).

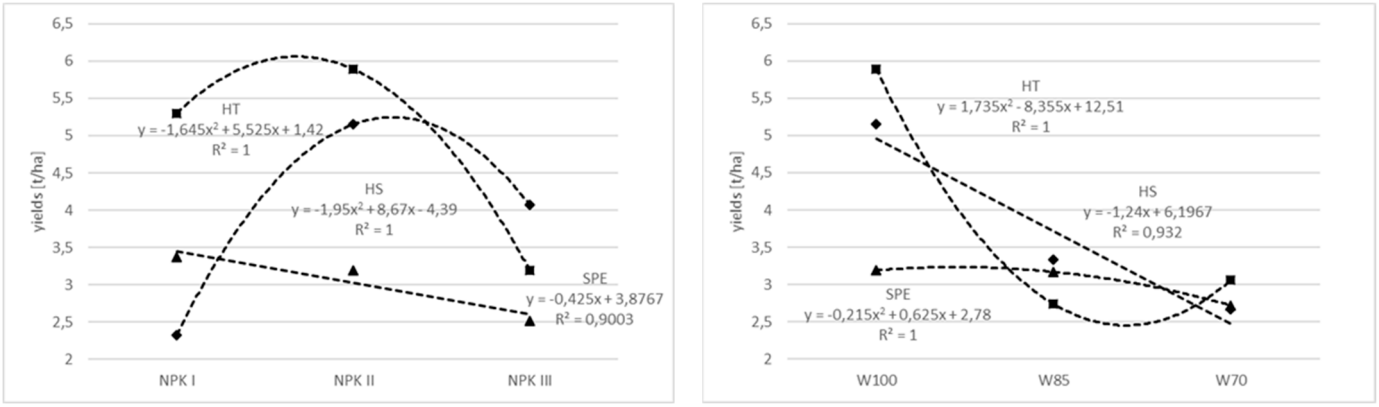
Table 3. Dependence of dry matter on fertilization and soil irrigation perennials yields.

Plant Species	Dry Mass of the Sample (t/ha)					
	NPK I	NPK II	NPK III	W 100	W 85	W 70
HS	2.33 ± 0.27	5.15 ± 0.93	4.07 ± 0.14	5.15 ± 0.93	3.33 ± 0.33	2.67 ± 0.09
SPE	3.37 ± 0.14	3.19 ± 0.60	2.52 ± 0.23	3.19 ± 0.60	3.17 ± 0.14	2.72 ± 0.05
HT	5.30 ± 0.23	5.89 ± 0.24	3.19 ± 0.42	5.89 ± 0.24	2.74 ± 0.52	3.06 ± 0.23

Among the tested plants, the highest hunting was obtained with grass plants after the first year of yielding. A significant increase in yield was recorded in all tested cases. Relative to the control trial, the depleted fertilizer rate resulted in a yield decrease of −4% to −32% and the enriched one in an increase of 5–33%. Water stress was distributed in a linear fashion (Figure 3). For each 15% depletion of the water dose, yield decreased absolutely 1.3 to even 1.9 t/ha and relatively from 9 to 26% (Table 4).

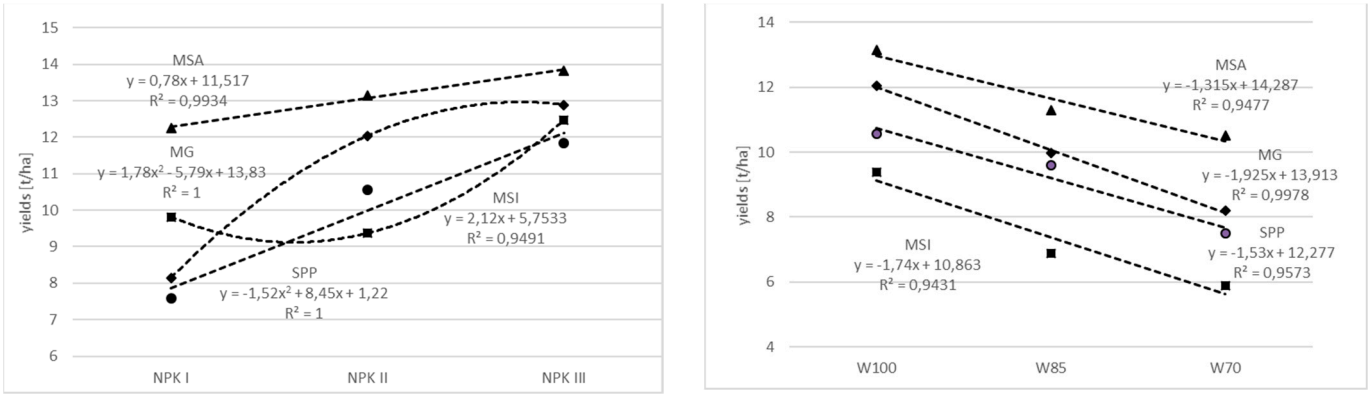
Table 4. Dependence of dry matter on fertilization and soil irrigation grass yields.

Plant Species	Dry Mass of the Sample (t/ha)					
	NPK I	NPK II	NPK III	W 100	W 85	W 70
SPP	8.15 ± 0.37	12.04 ± 0.76	12.89 ± 0.68	12.04 ± 0.76	9.96 ± 1.17	8.19 ± 0.37
MSA	12.26 ± 0.37	13.15 ± 0.29	13.82 ± 1.22	13.15 ± 0.29	11.30 ± 0.38	10.52 ± 1.05
MG	9.82 ± 0.55	9.37 ± 0.92	12.48 ± 1.53	9.37 ± 0.92	6.89 ± 0.73	5.89 ± 0.64
MSI	7.59 ± 1.06	10.56 ± 0.18	11.83 ± 0.14	10.56 ± 0.18	9.59 ± 0.34	7.50 ± 0.05



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

Figure 2. Change in yield of perennials in relation to (**a**) fertilization and (**b**) hydration.



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

Figure 3. Change in yield of grasses in relation to (**a**) fertilization and (**b**) hydration.

According to literature data, SPP yields can vary in the first three years after plantation establishment between 0.78 and 10.95 t/ha [55], 1.67–11.48 t/ha dry matter [28]. On the other hand, Budzyński and Bielski [56] report that yields from 17 to 29 t of dry matter can be obtained from 1 ha of the plantation. In our own studies, dry matter yields of prairie spartina ranged from about 8.2 to 12 t/ha. The highest SPP yield was obtained in the first year of the study at a growing season water rate of 513 mm. In a study conducted in the north-eastern part of Poland during a three-year study cycle, the highest yield (ca. 11 t/ha dry matter) was obtained in the third year of the study when the annual precipitation was the lowest at 481 mm [28].

Among the species of the genus Miscanthus, the highest yield in the conducted two-year studies (mean dry matter yield from all water variants) was recorded for MSA. In studies conducted in the north-eastern part of Poland, MSA was the highest yielding grass species among the cultivated ones (SPP, MSI and MSA). Its yields obtained in this region were on average about 9 t/ha [28]. In an 11-year study conducted by Dubis et al. [57], also in the north-eastern part of Poland, an average MSI biomass yield of 9.3 t/ha was obtained, the maximum yield was obtained in the last year of the study, and it was 14.4 t/ha dry matter, this year was characterized by the highest rainfall of 940 mm. In our study, MSI yields obtained ranged from 8 t/ha (in the variant with the lowest water dose) to 12.9 t/ha (at the highest fertilizer dose). MSA yielded the highest under conditions of the total water dose in the growing season above 500 mm, while a decrease in the amount of water resulted in a decrease in plant yield. The high sensitivity of MSA to water deficit was confirmed by Gauder et al. [58]. In their study, they obtained a reduction in bio-mass yield from 12

to 8 t/ha dry matter when rainfall decreased from 543 to 262 mm during two consecutive years of study.

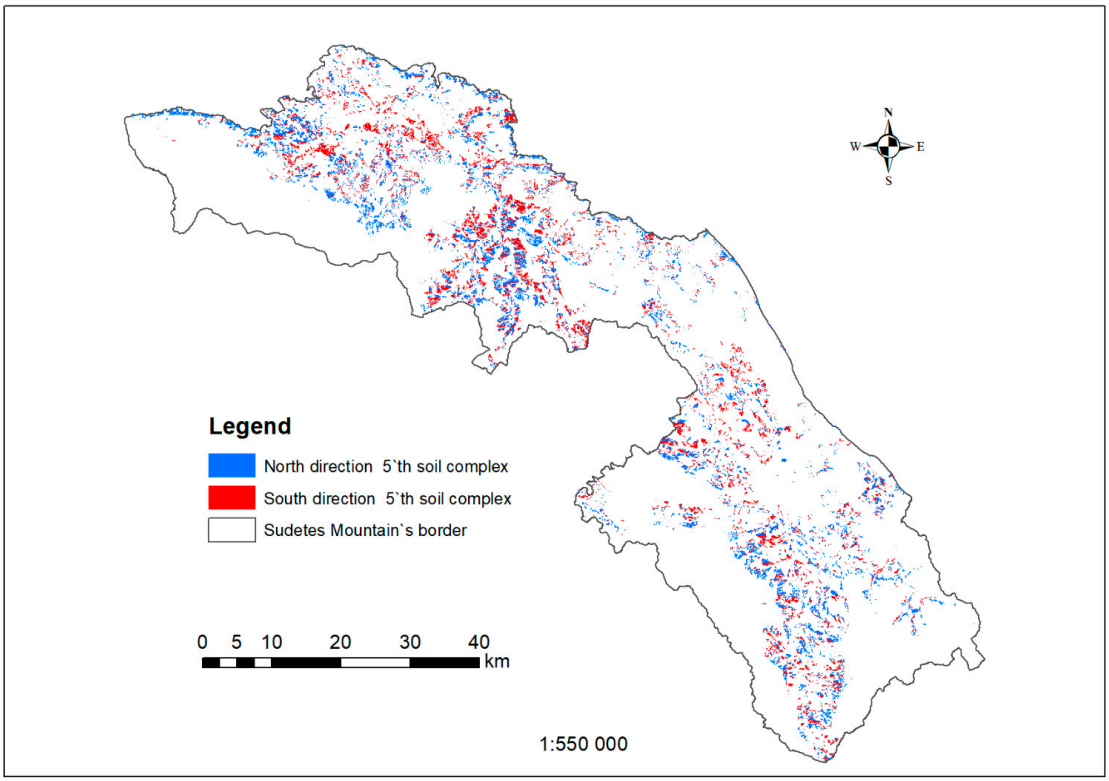
Another species in our study was MSI, whose yields ranged from 7.6 to 11.8 t/ha of dry matter. MSI is a species that, according to Jeżowski [59], can produce satisfactory yields at the level of 26.8 t/ha in cool climatic zones, especially in years with high summer temperatures.

The last species from the grass group grown in the experiment was MG. In studies conducted in Poland, obtained dry matter yields of MG (after reaching full production potential) ranged from 16 to 29 t/ha [60–63]. Matyka and Kuś [64], in a long-term study, obtained yields of 25–36 t/ha depending on the soil type, on light soil at 26 t/ha. In a study by Stolarski [28] in north-eastern Poland, MG also yielded lower than MSI and MSA and SPP. On the other hand, in a long-term study conducted by Dubis et al. [57] also in north-eastern Poland, the yield of MG was lower only in the first two years of cultivation in relation to the yield of MSA, and in the remaining years, it significantly exceeded it. In this study, the average yield for MG was 15.5 t/ha and for MSA 9.3 t/ha. In a study conducted on light soil in the south-western part of Poland (in Lower Silesia) [65], MG yields were the lowest in the first year of the study and ranged from 23.9 to 28.8 t/ha of dry matter over the three-year study cycle. According to Gauder et al. [58] water availability is a key factor in building MG yield. In a long-term experiment conducted by Dubis et al. [57], the highest yields of 19.0–20.0 t/ha were obtained in years with the highest rainfall (750 and 940 mm), while yield reductions were recorded in years with the lowest rainfall below 500 mm (454 and 492 mm). The results of our study indicate that the yield of dry matter MG depended on the amount of water supplied to plants and decreased with its reduction. The highest yield of 12.5 t/ha was obtained at an annual water quantity of 520 mm. A decrease in irrigation doses resulted in a decrease in MG yields. The lowest yields were recorded at the dose of 400 mm (5.9 t/ha).

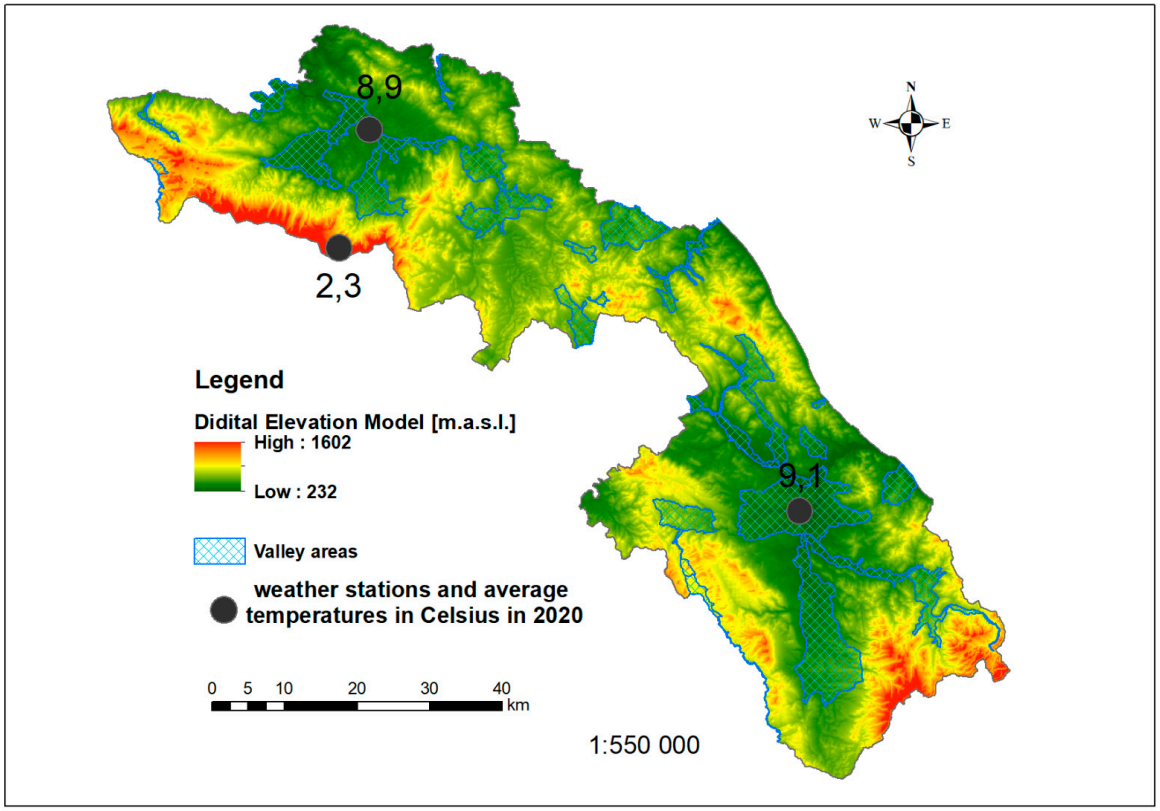
5. Results of Biomass Potential Studies Using GIS

Mountain farming, due to unfavorable natural factors, is not very profitable. In Poland, the costs of cereal production in these areas are between 30% and even 50% higher than in lowland areas. This also applies to the Sudetenland, which has different characteristics from other mountainous areas. After 1945, as a result of a complete population change, there was a break with agricultural traditions in this region, which contributed, among other things, to the set-aside of around 30% of agricultural land and the depopulation of mountain villages. In the conditions of the market economy, this process was aggravated by the collapse of state farms and production cooperatives. The development programs implemented today are aimed at supporting sustainable farming, in which environmental protection is not at odds with the economic development of the rural population.

The Polish part of the Sudeten Mountains has an area of 370,692 ha, of which 95,341 ha is arable land. A significant part of the arable land is low-quality soil. The soils of the 5th quality level examined in this study cover the area of 35,726 ha, which is as much as 37.47% of the total arable land. Growing lignocellulosic crops on low-bonation (marginal) areas is justified from the point of view of food overproduction in the European Union. It is also important that crops grown on marginal land will provide a sustainable alternative to growing food crops on more fertile land, at the same time stimulating the agricultural development of the mountain economy without having to compete with lignocellulosic crops on arable land. Unfavorable climatic conditions for biomass cultivation have been identified in the literature. Based on the analysis of biomass potential in Romania, it was found that the mountain regions are characterized by high precipitation, but due to the average low temperature (4–5 °C) the biomass yield is not satisfactory [66]. Compared to the Carpathians, the Sudetenland is a much lower mountain range (highest peak Śnieżka 1603 m) where average annual temperatures reach 9 °C (Figure 4b) and average annual precipitation 900 mm (Institute of Meteorology and Water Management 2020).



(**a**)



(**b**)

Figure 4. Presentation of the Polish Sudetes: (**a**) spatial distribution of marginal soils; (**b**) terrain relief and mean annual temperature values.

The marginal lands under study are located in the valleys of the Sudeten Mountains, where favorable climatic conditions prevail. We know from local intelligence that in the Kłodzko County there are numerous plantations of energy crops, mainly energy willow. Crops are located among others in the villages: Gorzanów, Kamieniec, Ołdrzychowice Kłodzkie, Kudowa-Jeleniów. The areas of these plantations, ranging from 3 to 25 ha, are located on soils of low quality, where the humus layer does not exceed 15 cm. Farmers receive EU subsidies for farming in difficult conditions due to unfavorable terrain and benefit from a service which provides the necessary equipment for harvesting and transporting directly to the point of destination (in this case, the Opole power plant).

The plant types selected for the study divided into two groups. The first group can be plants on the northern exposure due to the much cooler climate and local frosts. This group includes *Populus nigra, Salix purpurea, Salix viminalis, Robinia pseudoacacia, Helianthus salicifolius, Silphium perfoliatum, Helianthus tuberosus*. On the southern side, the grasses *Spartina pectinate, Miscanthus sacchariflorus, Miscanthus giganteus, Miscanthus sinensis* can used. The area of arable land of the 5th quality grade in the Sudeten Mountains with northern exposure is 19,030 ha, southern exposure is 16,696 ha. The distribution of fields is shown in Figure 4. In the north-eastern part of the Polish Sudetes, there are areas with a larger average area of shelves and greater abundance due to more favorable terrain. The south-eastern part includes the area of the Kłodzko Valley and more fertile soils used for agriculture.

On the basis of plant yield data (Table 5), an analysis was undertaken for dry biomass harvesting from marginal land in the Polish Sudeten Mountains. Table 5 shows the estimated yield depending on the planting species. The highest biomass harvest can be obtained by sowing HT on fields with northern exposure and MSA on fields with southern exposure. Our study shows that after the first year, the dry biomass harvest would be 331,639 tons/year from 35,762 ha giving an average of 9.27 tons/ha. The lowest yield was estimated for PN and MG in the same exposure configuration 210.106 tons, i.e., average yield is 5.86 tons/ha. If the level of fertilization is not high, i.e., NPK I, the most favorable planting density is the combination of MSA with RP or HT, which gives yields of 299,082 and 305,552 tons/year of dry matter, respectively. In contrast, when fertilization is increased to NPK III, the summed dry biomass from HT and MSA will result in a decrease of 12.1% yield. For NPK III, high yields were obtained with RP and SP with all grass crops ranging from 297,611 to 335,023 tones/year. Compared to GIS estimation data of selected Polish and Italian provinces, yield results obtained are higher [9,27]. Table 5 shows that water stress has the most significant impact on biomass yield. The precipitation in the Polish Sudeten Mountains is higher than 500 mm every year, therefore, the results may be valuable for estimating the amount of biomass in areas with less intense precipitation. Both the amount of precipitation and the lie of the land favor the introduction of perennial energy crops, the cultivation of which does not require the annual establishment of plantations.

Table 5. Biomass yield and the effect of fertilization and irrigation on yield in the Polish Sudeten mountains.

	SPP	**MSA**	**MG**	**MSI**				
	NPK I							
PN	−26.4%	−6.3%	2.5%	−22.6%				
SP	−27.4%	−9.4%	−2.6%	−24.2%				
SV	−26.9%	−7.6%	0.2%	−23.3%	SPP	MSA	MG	MSI
RP	−23.8%	−6.8%	0.2%	−20.4%		NPK II W 85		
HS	−39.7%	−21.6%	−18.1%	−37.6%	−17.0%	−14.4%	−23.8%	−10.8%
SPE	−23.5%	−4.1%	5.0%	−19.5%	−15.0%	−12.8%	−20.5%	−9.3%
HT	−24.3%	−7.9%	−1.4%	−21.1%	−13.0%	−10.8%	−18.5%	−6.7%
	NPK II W 100 [tone of dry biomass]				−15.2%	−13.1%	−20.4%	−9.9%
PN	254,684	273,217	210,106	229,974	−23.2%	−20.6%	−29.9%	−18.5%
SP	286,655	305,187	242,077	261,945	−13.4%	−11.2%	−19.2%	−7.0%
SV	268,005	286,538	223,427	243,295	−30.2%	−27.4%	−37.7%	−26.4%
RP	302,450	320,982	257,871	277,740		NPK II W 70		
HS	299,024	317,557	254,446	274,314	−31.1%	−21.5%	−34.7%	−28.7%
SPE	261,726	280,258	217,147	237,015	−33.6%	−24.9%	−37.3%	−31.8%
HT	313,107	331,639	268,528	288,396	−31.7%	−22.5%	−35.2%	−29.4%
	NPK III				−31.3%	−23.1%	−34.3%	−29.3%
PN	8.3%	6.7%	28.1%	12.3%	−37.3%	−28.7%	−41.4%	−35.8%
SP	10.0%	8.4%	27.4%	13.6%	−28.0%	−18.9%	−30.9%	−25.3%
SV	6.4%	4.9%	24.5%	9.9%	−37.7%	−29.5%	−41.7%	−36.4%
RP	5.6%	4.4%	21.2%	8.7%				
HS	−2.1%	−2.9%	12.3%	0.2%				
SPE	0.6%	−0.6%	18.0%	3.6%				
HT	−11.9%	−12.1%	0.2%	−10.5%				

To better illustrate the effect of fertilization level on biomass yield, the results are presented in graphical form (Figure 5). An increase in fertilization increases the yield of shrubs, trees, and perennials. In the following years of cultivation, the difference between the yield of grasses and other perennial plants will decrease. An increase in fertilization results in a higher yield of trees, perennials, and shrubs with a proportionally lower increase in the yield of grasses. Figure 5 shows a significantly higher yield of PR and HT with MSA. Under normal NPKII fertilization, yield differences are significantly lower, worst at PN, SV, and SPE planting with MG. Increasing fertilization increases the yield of those plants where biomass yield was lowest with NPK I and NPK II.



Figure 5. Biomass yields in relation to cultivation of plant types.

6. Conclusions

The yield of perennial plants is highest after several years of cultivation. Pot experiments show that yields can already benefit after the first year. The lowest yield was observed for trees and shrubs at 2.82 (Populus nigra) to 5.33 (Robinia pseudoacacia) tons/ha and for perennials at 3.19 (Silphium perfoliatum) to 5.89 (Helianthus tuberosus) tons/ha. The first year grass yield was much higher, 9.73 (Miscanthus giganteus) to 13.15 (Miscanthus sacchariflorus) tons/ha.

Based on the yield data from pot experiments and the land area available for perennial crops, the dry matter yield after the first year of cultivation was calculated. The arable land area in the Polish Sudetenland is 95,341 hectares, of which 35,726 hectares are in the soil of the 5th quality class. Due to the steep slopes of the land and the quality class, the cultivation of annual crops is unprofitable. In addition, the Polish Sudetenland is a region characterized by high levels of precipitation, above 500 mm, which favors the growth of biomass. Planting this area with perennial plants, in this case, is justified. The analysis was carried out taking into account the slope of the terrain on the northern exposure of 19,030 hectares and on the southern exposure of 16,696 hectares. It is recommended to

seed the southern exposure with grasses and the northern exposure with trees, shrubs and perennials because of their greater resistance to low temperatures and less sunshine. It has been estimated that after the first year of cultivation, Helianthus tuberosus and Miscanthus sacchariflorus can be expected to yield 331,639 tons of dry matter with standardized fertilization; any other plant configuration will reduce yield by up to 37%. A change in fertilization will cause a significant yield change in low-yielding plants. Water stress has the most significant effect on yield up to 41%, but in the case of the Polish Sudeten Mountains, this factor is not taken into account. The investigated water stress will give the possibility to estimate the yield in areas with low precipitation intensity.

The results obtained indicate that the sowing structure has a significant influence on the biomass production volume in the analyzed region. This study requires further analysis to determine the profitability of production. As Maulogianni et al. present in their study, the decision of the right choice of plantation type has a significant impact on the profitability of biomass production [67,68]. The results of the research presented in this paper are a source of data for further analysis from an economic point of view.

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