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Biomass as an Energy and Natural Resource in Mineral Habitats of Post-Mining Areas

Jakub Ceglarek [1], Damian Chmura [2], Agnieszka Hutniczak [3], Agnieszka Błońska [3], Roman Dychkovskyi [4,5], Artur Dyczko [6], Paweł Kamiński [7] and Gabriela Woźniak [3,*]

[1] Environmental Remote Sensing and Soil Science Research Unit, Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, Krygowskiego 10, 61-680 Poznan, Poland; jakub.ceglarek@amu.edu.pl
[2] Institute of Engineering Sciences, Faculty of Materials, Civil and Environmental Engineering, University of Bielsko-Biala, 2 Willowa Str., 43-309 Bielsko-Biała, Poland; dchmura@ubb.edu.pl
[3] Institute of Biology, Biotechnology and Environmental Protection, Faculty of Natural Sciences, University of Silesia in Katowice, 28 Jagiellońska Str., 40-032 Katowice, Poland; agnieszka.hutniczak@us.edu.pl (A.H.); agnieszka.blonska@us.edu.pl (A.B.)
[4] Department of Mining Engineering Mineral Resources, Dnipro University of Technology, 19 Yavornytskoho Ave., 49005 Dnipro, Ukraine; dychkovskyi.r.o@nmu.one
[5] Faculty of Management, AGH University of Krakow, 30 Adama Mickiewicza Al., 30-059 Krakow, Poland
[6] Mineral and Energy Economy Research Institute, Polish Academy of Sciences, 7A J. Wybickiego Str., 31-261 Kraków, Poland; arturdyczko@min-pan.krakow.pl
[7] KOMAG Institute of Mining Technology, 37 Pszczynska Str., 44-101 Gliwice, Poland; pkaminski@komag.eu
* Correspondence: gabriela.wozniak@us.edu.pl

Abstract

This manuscript investigates the energy potential of spontaneously developing vegetation in post-mining areas by integrating field biomass measurements, calorific characterization, environmental variables, and satellite-based biomass estimation. This approach offers a potentially valuable contribution by linking bioenergy resource assessment with the ecological functions of recovering ecosystems. Biomass is an important renewable energy resource, but its assessment is often based mainly on yield and calorific value. In post-mining landscapes, however, biomass develops spontaneously through ecological succession and simultaneously contributes to carbon storage, soil formation, habitat development, biodiversity increase, and ecosystem functioning. This study assesses spontaneously produced plant biomass in mineral post-mining habitats by integrating biomass yield, calorific value, energy potential, carbon balance, functional traits, and habitat conditions. Vegetation representing different successional stages is analysed to determine how environmental constraints influence biomass quantity and quality. The proposed framework supports sustainability-oriented assessment of bioenergy potential while considering biodiversity, ecosystem functions, carbon retention, and regenerative capacity. Stands dominated by *Calamagrostis epigejos* and *Solidago gigantea* had similar values and were characterised by relatively high biomass. Intermediate biomass values were observed in communities dominated by *Centaurea rhenana*, *Daucus carota* and *Tussilago farfara*. Particle-size fractions, particularly sand and gravel, contributed to sample separation along both PCA dimensions. Soil moisture showed a strong association with the upper portion of the ordination space, indicating an important moisture gradient underlying vegetation differentiation.

Keywords: spontaneous vegetation biomass; post-mining sites; mineral habitats

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1. Introduction

Biomass is traditionally viewed primarily as a renewable energy resource—a potential alternative to fossil fuels and a component of the transition toward low-emission energy systems. In this context, plant biomass is treated as an energy carrier that can be used directly or converted into biofuels, biogas, bio-oils, biochar, or thermal and electrical energy. However, the significance of biomass stems not only from its energy value but also from its origin, the method of its acquisition, and the functions it performs within the ecosystem before its utilisation. Indeed, contemporary analyses of the sustainable use of biomass indicate that its energy value cannot be assessed in isolation from its impact on soil, water, biodiversity, carbon cycle, and ecosystem functioning [1].

This problem becomes particularly important in post-mining areas, where biomass is not the result of planned agricultural or forestry production but may arise spontaneously through ecological succession. Mineral post-mining habitats, including heaps, dumps, excavations, subsidence basins, and areas following the exploitation of sand, coal, or metal ores, are often perceived as degraded and in need of recultivation. At the same time, growing research results indicate that some of these places are developing their own ecosystem development trajectories, in which spontaneous plant colonisation leads to the emergence of new ecosystem systems, often different from the ecosystems that existed before exploitation [2]. Spontaneous succession can contribute to the development of vegetation cover, the accumulation of organic matter, the development of microorganisms and the gradual creation of a functional soil profile [3,4].

In this context, plant biomass generated in mineral post-mining habitats should be considered a dual resource—energy and natural. On the one hand, it represents a specific amount of chemical energy stored in plant tissues, which can be used as an energy resource. On the other hand, it is a material component of a developing ecosystem, participating in carbon sequestration, organic matter production, habitat creation, soil stabilisation, microclimate regulation, and the maintenance of food webs. Therefore, its removal may mean simultaneously obtaining an energy resource and losing some of the ecological functions of the developing ecosystem.

The importance of spontaneously produced biomass is particularly evident during succession on post-mining dumps. Initially, the vegetation develops under conditions of severe habitat constraints, including a deficiency of water, organic matter, and nutrients, high surface temperatures of the mineral substrate, and often unfavourable pH and salinity. Regardless of the favourable habitat conditions of the mineral material of post-mining sites, plants and other organisms colonise in the first year after heaping. With time, vegetation develops spontaneously, biomass production increases, and dying plant parts become a source of litter and organic matter. This process may trigger feedback between vegetation development and the shaping of soil properties. Research conducted in areas after lignite mining showed the development of the fermentation and humus layers with the progression of succession, as well as changes in the organisation of the soil food network [5,6].

At the same time, biomass that arises spontaneously in post-mining areas may represent a significant energy potential. As succession develops, the share of grasses, perennials, shrubs, and trees increases, and, in later stages, also the share of woody biomass. Research on post-mining areas indicates that the development of spontaneous vegetation may create significant resources of above-ground biomass. In the case of coal mining dumps, the important role of successional vegetation in carbon storage has also been demonstrated, and comparisons of various management methods indicate that succession may be an alternative pathway for managing carbon resources in biomass and soil [7].

It is therefore worth moving away from the approach in which the value of biomass is seen primarily in its productivity and energy potential. A more comprehensive approach

should also account for the variability in biomass properties and the potential to adapt conversion and control processes to changes in fuel characteristics [8,9]. Previous studies have shown the potential of neural and neuro-fuzzy control systems to improve the energy performance of solid biofuel production and to develop resource-saving operating modes of bioheat generators under variable process conditions [2]. In post-mining areas, the "biomass multifunctionality" approach is more appropriate, in which the same unit of biomass simultaneously performs energy, habitat, water retention, soil-forming, ecosystem developmental stage and landscape functions. This approach gives a broader framework for assessing the trade-offs between bioenergy resources and the protection of biodiversity and ecosystem functioning as the prerequisites of ecosystem services. Research indicates that these relationships are highly contextual, and previous land use, biomass type and management methods may determine whether biomass use generates synergies or conflicts between applied and nature goals [10].

In this paper, biomass is defined as the one-season above-ground plant photosynthesised biomass, established spontaneously in a particular vegetation-type patch. Biomass, defined in this way, serves as both an energy resource and an important ecosystem function parameter.

The biomass of vegetation patches in a developing novel ecosystem reflects the efficiency of matter and energy flow within those ecosystems. Autotrophic organisms, primarily phototrophic plants, are the only primary components that convert sunlight into the energy stored in the biochemical bonds between carbon atoms within ecosystem biomass. Biomass results from the synthesis of inorganic compounds, driven by plants' ability to capture sunlight [11–13]. The biomass synthesis process, the matter, the biomass establishment and circulation, and the matter–energy flow depend on many factors. The prerequisites for biomass synthesis include characteristics of vegetation species composition, which determine the amount of biomass synthesised. The biodiversity of vegetation species composition directly affects biomass and, indirectly, all ecosystem processes [11–13].

Higher biodiversity, in general, is predicted to increase biomass parameters and ecosystem stability. Two of the upper limits of biomass primary production are the biotic and abiotic environmental factors [14,15]. According to current research, plant biomass increases with diversity, but after a certain point, it decreases. The decrease in diversity occurs because vegetation communities with high biomass are frequently dominated by a small number of highly productive, competitive species (often a single species) [16]. The question remains open as to whether high community biomass is causing the decrease in biodiversity, or the opposite: decreasing autotroph diversity increases the amount of synthesised biomass [17,18]. Some studies have revealed that ecosystem vegetation species composition, diversity, and biomass depend on below-ground and above-ground conditions and on the biotic processes that drive ecosystem functioning [19,20]. Autotrophic species diversity and enzyme activity reflect soil microbial activity, which is linked to biomass biochemistry. The biochemistry of the biomass depends on the plant species composition of the vegetation, characterised as the vegetation type plant species [17,18]. The biochemical composition of biomass results from the plant species composition of the vegetation types, shaped by biotic habitat conditions [19,20]. Vegetation plant species composition, including above- and belowground parts, affects rhizosphere root exudates and soil gas exchange [16–18].

Therefore, spontaneously synthesised biomass in mineral post-mining habitats can be conceptualised as a dynamic natural resource whose value changes over time as succession develops. In the early stages, its most important function may be to initiate the accumulation of organic matter and stabilise the substrate. In contrast, in later stages, its importance increases as a carbon store and a potential source of woody biomass. At the same time, some biomass may have high environmental value regardless of its energy value. This means

that maximising biomass production should not be automatically equated with maximising ecosystem value.

Consequently, the dual role of spontaneously synthesised biomass becomes an important issue for a new model of post-mining area management. Instead of treating succession as a process that only leads to the "greening" of mining-disturbed areas. It should be seen as the creation of new natural capital, with biomass among its measurable results. At the same time, part of this capital can be used economically, provided that biomass acquisition does not exceed the system's ecological capacity to reproduce it and does not limit key ecosystem functions. This approach combines the goals of energy transformation, circular economy, carbon sequestration and biodiversity protection. Previously, the potential of spontaneous vegetation as a biomass energy source has not been considered; consequently, no models have been developed to capture the process. So no comparison between the classical models and the model applied in this study can be described. A non-classical model for the post-mining site vegetation as a biomass energy source exists because no one has treated spontaneously established vegetation as a potential biomass source for energy.

The mineral post-mining habitats become established as a result of the exploitation of the black hard coal energy resource. In this respect, post-mining sites are an inherent part of the energy resource extraction process. On the other hand, at the post-mining sites, the established plants and assembled vegetation are synthesising biomass. In this paper, we focus on the traits of spontaneously synthesised biomass as a parameter of ecosystems (novel ecosystems) developing on post-mining sites. The amount, trait characteristics, habitat conditions and dynamics of selected spontaneous vegetation types will be analysed. In addition to the standard functional traits of the studied species, the energy potential of its biomass will be analysed.

2. Materials and Methods

2.1. Study Area

The study area encompasses three post-mining heaps, located around the Upper Silesian industrial district: Sośnica (A) in Gliwice, Murcki-Boże Dary (B) in Katowice and Wesoła (C) in Mysłowice (Figure 1). Field surveys, including vegetation-cover assessment and above-ground biomass sampling, were carried out in July 2016 and during the project TANGO (TANGO1/268600/NCBR/2015; 1 July 2015–31 May 2019), and continued in two PhD projects and the project OPUS-18 (2019/35/B/ST10/04141; 3 August 2020–3 August 2024). The region in southern Poland is described as having a moderate continental climate, with mean annual temperatures around 8.5 °C. July is the warmest month, with mean temperatures of 17.5 °C to 18.5 °C, while January is the coldest, averaging −1.5 °C to −3.0 °C. The annual precipitation ranges between 650 mm and 800 mm, with the peak rainfall during the summer months and late winter/early spring having the least amount of rainfall. The growing season averages 210 to 220 days.

The studied post-mining heaps consist of heterogeneous carboniferous coal-mining waste containing mineral and residual carbonaceous fractions. Reactive carbonaceous material and minerals such as pyrite can promote self-heating and spontaneous thermal activity in hard-coal spoil heaps. Furthermore, the physical properties of carboniferous spoil substrates, including bulk density, porosity, capillary water capacity, and soil-water storage, can constrain root development and water availability, thereby contributing to stressful conditions for vegetation.

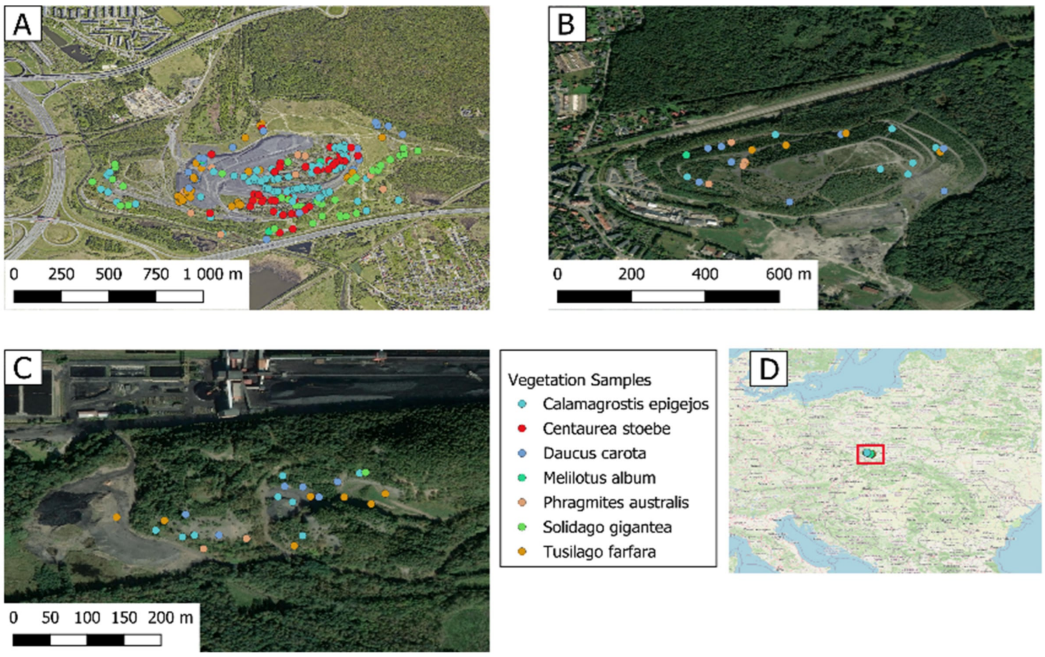


Figure 1. The distribution of the study plots on the three studied heaps, Sośnica (**A**), Murcki-Boże Dary (**B**), Wesoła (**C**); the locality of the studied heaps in Europe (**D**).

2.2. Biomass Sample Collection

Fieldwork was conducted during a single growing season. Plant samples were collected from four post-mining heaps in the Katowice Upland. Research plots were established as circles with a 3 m radius within a homogeneous vegetation patch dominated by a specific dominant species. A species was classified as dominant if it occupied the largest surface area within the established plot compared to the rest of the vegetation. Data collected from each plot included a floristic inventory with percentage vegetation cover estimates (up to 30% of vegetation cover, 30–60%, and over 60%) for the herbaceous layer and necromass, and measurements of soil pH and moisture. For the pH and moisture measurements, 5 subsamples were collected at the root depth in each plot from which biomass was collected.

The spontaneous development of vegetation patches on post-mining sites meets all the prerequisites for novel ecosystem vegetation. That means the vegetation has a non-analogous species composition on the extreme mineral material of the post-mining sites. One characteristic of newly established vegetation patches is near-monospecific dominance. To avoid any doubts about our previous study, we have defined the one-species-dominated vegetation type (patch) as a patch in which the dominant plant cover exceeds the sum of the cover of all other species in the patch.

The geographic coordinates of the centre point of each study area were recorded using a GPS receiver (Garmin OREGON 550t, Poland). A representative square was designated within the research plot—that is, one containing the dominant species and best representing the entire patch (in terms of the dominant species' cover and the quantitative relationships between the dominant species and co-occurring species). The research plot had a side length of 0.5 m (Figure 2).

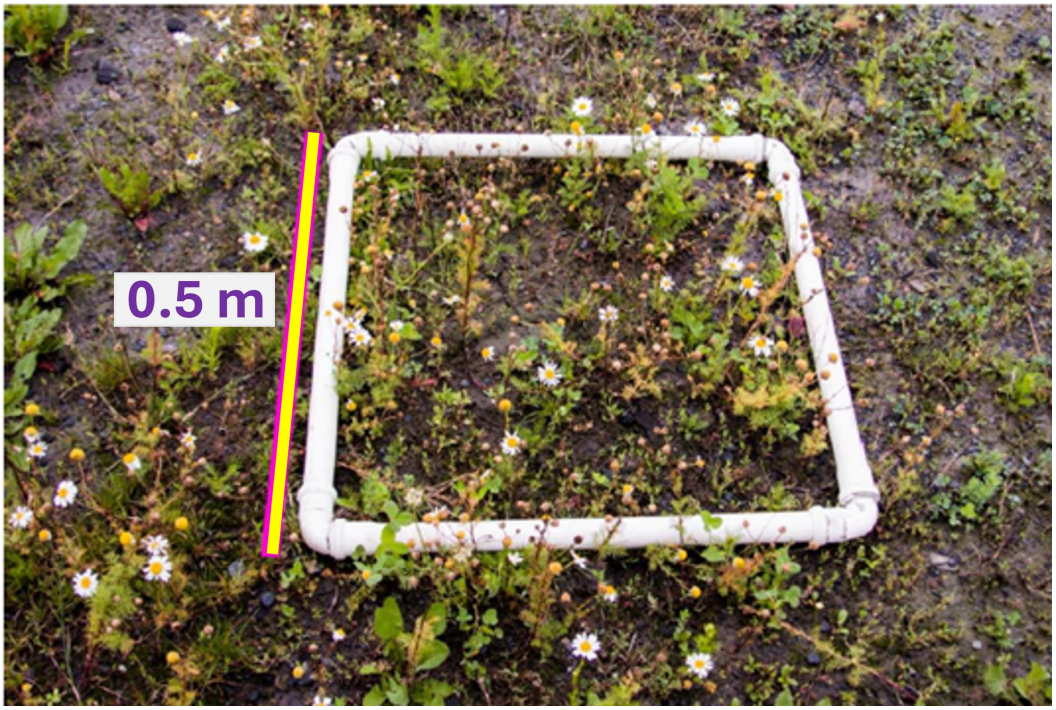


Figure 2. The frame used for the above-ground biomass collection. Designated study quadrat (Phot. G. Woźniak).

Figure 2 presents the frame that has been used to indicate the 0.5 × 0.5 m vegetation patch area from which the above-ground parts of the plants have been collected for the biomass measurements. All the plants in the frame were collected regardless of height.

The above-ground parts of the plants were harvested from the designated area, with the dominant species carefully separated from the other plant species. The plants were cut using garden shears.

The analysis of this paper will focus on a few selected species. From all recorded vegetation plots, the following dominant plants have been selected for this study: two grasses: *Calamagrostis epigejos* and *Phragmites australis*; herbaceous species: *Daucus carota*, *Centaurea rhenana*, *Tussilago farfara*, *Melilotus albus* (legume); and one alien plant species. *Solidago gigantea*. This dominant species represents the microhabitat mosaic present on the post-mining mineral habitats.

2.3. Calorific Value Parameters

The calorific values of the selected plant species were determined using an automated bomb calorimeter IKA C 200 (IKA-Werke GmbH & Co. KG, Staufen Germany) following standard analytical procedures (e.g., in accordance with EN 14918 for solid biofuels or equivalent standard procedures for biomass energy determination).

Prior to analysis, representative plant biomass samples were air-dried and subsequently ground in a cutting mill (Morek Multiserw, Brzeźnica, Poland) to pass through a 1 mm mesh screen. The analytical samples were then oven-dried to a constant weight at 105 ± 2 °C to ensure completely dry substance (s.m., dry mass). For each plant species, analytical measurements were performed in triplicate (n = 3) using a sample mass of approximately 0.8–1.0 g of dry powder and pelleted prior to combustion. The calorimeter was calibrated using benzoic acid as a certified reference standard.

The values of net calorific value (NCV) of the dry biomass reflect the maximum theoretical primary energy potential based on yield and calorific value.

2.4. Sentinel-2 Data Acquisition and Processing

The multi-year Sentinel-2 time series was processed in Google Earth Engine. Level-2A bottom-of-atmosphere surface-reflectance data were obtained using the COPERNICUS/S2_SR_HARMONIZED collection for the period from March 2016 to August 2026 [21]. Although the Earth Engine Data Catalog lists this collection as available from 28 March 2017, metadata inspection identified the 2016 observations as historical Level-2A products (S2A_MSIL2A) generated during the Collection-1 reprocessing campaign with processing baseline 05.00. The analysis included the visible bands B2–B4, red-edge bands B5–B7, near-infrared bands B8 and B8A, and shortwave-infrared bands B11 and B12. Cloud- and shadow-affected pixels were excluded using the Level-2A Scene Classification Layer. The spectral bands were resampled to a common spatial resolution of 10 m, and valid observations were organized into 15-day temporal intervals.

The obtained spectral data were used in the calculation of the following spectral indices:

For each sampling point and year, annual summary statistics were calculated from all valid individual Sentinel-2 observations. These included the annual mean, the 90th percentile, and the annual maximum. The annual maximum was defined as the highest valid index value recorded for a given point-year and was therefore not the maximum of monthly averages. Because a single annual maximum may be sensitive to an anomalous observation, the 90th percentile was additionally included as a more robust measure of near-maximum seasonal vegetation condition.

Seasonal variation was represented separately using monthly medians calculated from all valid observations within each month from April to October. Monthly medians were used to reduce the influence of isolated extreme observations.

2.5. Biomass and Calorific Energy Potential Modeling

For each sampling location, the total dry biomass was defined as the sum of the dry biomass of the dominant and remaining vegetation. Total dry biomass over the years was modelled using pooled Ridge regression. Predictor variables included annual and monthly Sentinel-2 index summaries, dominant-species cover, total vegetation cover, and vegetation-group identity. The regularization parameter was fixed at $\alpha = 10$. Continuous predictors were median-imputed and standardized, while vegetation-group was represented by indicator variables. The model's performance was evaluated using leave-one-point-out cross-validation and reported as cross-validated R^2, MAE, RMSE, and prediction bias. The biomass model was calibrated using field-measured total dry biomass and corresponding Sentinel-2 predictors from 2016. Following calibration and cross-validation, the fitted relationship was applied without annual recalibration to corresponding Sentinel-2 predictor sets for 2017–2026. This transfer assumes that the relationships among total dry biomass, spectral response, vegetation cover, and vegetation-group identity remained approximately stable over the analysed period. No independent biomass measurements were available after 2016; consequently, temporal transferability could not be evaluated directly. The resulting values are therefore treated as exploratory model-based biomass reconstructions rather than validated annual biomass measurements.

The estimates of total dry biomass were converted from g/m^2 to t/ha by multiplying by 0.04. The theoretical energy potential was then calculated separately for each vegetation group and year by multiplying the biomass by the group-specific calorific value of dry matter. The energy calculation assumed that the group-specific calorific value remained constant over the analysed period and that the model-estimated biomass represented completely dry matter. The calculation describes gross theoretical energy content per unit area. Uncertainty in the reconstructed biomass trajectories was assessed using a point-level nonparametric bootstrap with 1000 replicates. In each replicate, the 146 calibration points were sampled

with replacement, and the complete preprocessing and pooled Ridge-regression pipeline was refitted. Median predictions and 2.5th–97.5th percentile intervals were calculated from the bootstrap distributions.

The analytical sequence was: field harvesting → measurement of fresh biomass → sample drying → measurement of dry biomass → calculation of total dry biomass → calibration of the remote-sensing biomass model → model-based biomass reconstruction → application of group-specific calorific values → calculation of theoretical energy potential in GJ/ha.

2.6. Statistical Analyses

Differences in fresh aboveground biomass among vegetation patches dominated by different plant species were assessed using the non-parametric Kruskal–Wallis test due to potential deviations from normality and heterogeneity of variances (Table 1). Pairwise comparisons among dominant species were performed using Dunn's post hoc test with Benjamini–Hochberg (BH) correction for multiple testing. Descriptive statistics were expressed as medians and interquartile ranges (Q1–Q3). Relationships among the environment, soil, and biological variables were explored using Spearman's rank correlation coefficient (r_s). Only significant correlations ($p < 0.05$) were visualised in the correlation heatmap.

Table 1. Spectral data used in the calculation of the spectral indices.

Spectral Index	Formula	Source
NDVI	B8 − B4/B8 + B4	[22]
GNDVI	B8 − B3/B8 + B3	[23]
NDMI	B8 − B11/B8 + B11	[24]
NBR	B8 − B12/B8 + B12	[25]
NDRE	B8A − B5/B8A + B5	[26]
CI_{red_edge}	B8A/B5- 1	[27]

Principal component analysis (PCA) was used to investigate multivariate patterns among sampling plots and to identify the variables contributing most strongly to the ordination space. PCA was based on standardised variables (zero mean and unit variance). Sampling plots were grouped according to dominant plant species and projected onto the first two principal components. Variable loadings were used to interpret ecological gradients associated with the ordination axes.

The relative importance of abiotic and biotic drivers of vegetation structure and productivity was assessed using variation partitioning based on redundancy analysis (RDA). Response variables included dominant species cover (Cover.dom), herbaceous layer cover (HerbCover), cryptogam cover (D.cover), species richness (S), and fresh aboveground biomass (Biomass.fresh). Explanatory variables were divided into two groups: (i) soil physicochemical properties (soil pH, moisture, nutrient concentrations, particle-size fractions, electrical conductivity, and bare soil cover) and (ii) biological properties (soil enzyme activities, soil fauna abundance, necromass and soil respiration SRL). The significance of individual fractions was tested using permutation tests (999 permutations). All analyses were performed in R (version 4.5.1. R Core Team 2025).

3. Results

The mineral habitats of the post-mining sites are by-products of the exploitation of coal energy resources. According to the latest study results, the post-mining sites represent the

potential of natural processes. The post-mining sites represent a few natural features, very rare oligotrophic habitats, which is why these sites provide refuge habitats for many species. In contrast to the suggested opinion, mineral habitats in post-mining sites are spontaneously colonised by diverse organisms, including autotrophic plant species, which assemble into vegetation patches that produce substantial biomass.

The habitat conditions that determine vegetation patch assembly, the distribution of vegetation patches, and the biomass established were studied in only a few papers.

3.1. Fresh Aboveground Biomass

Fresh aboveground biomass differed significantly among vegetation patches dominated by different plant species (Kruskal–Wallis test, $p < 0.05$) (Figure 3).

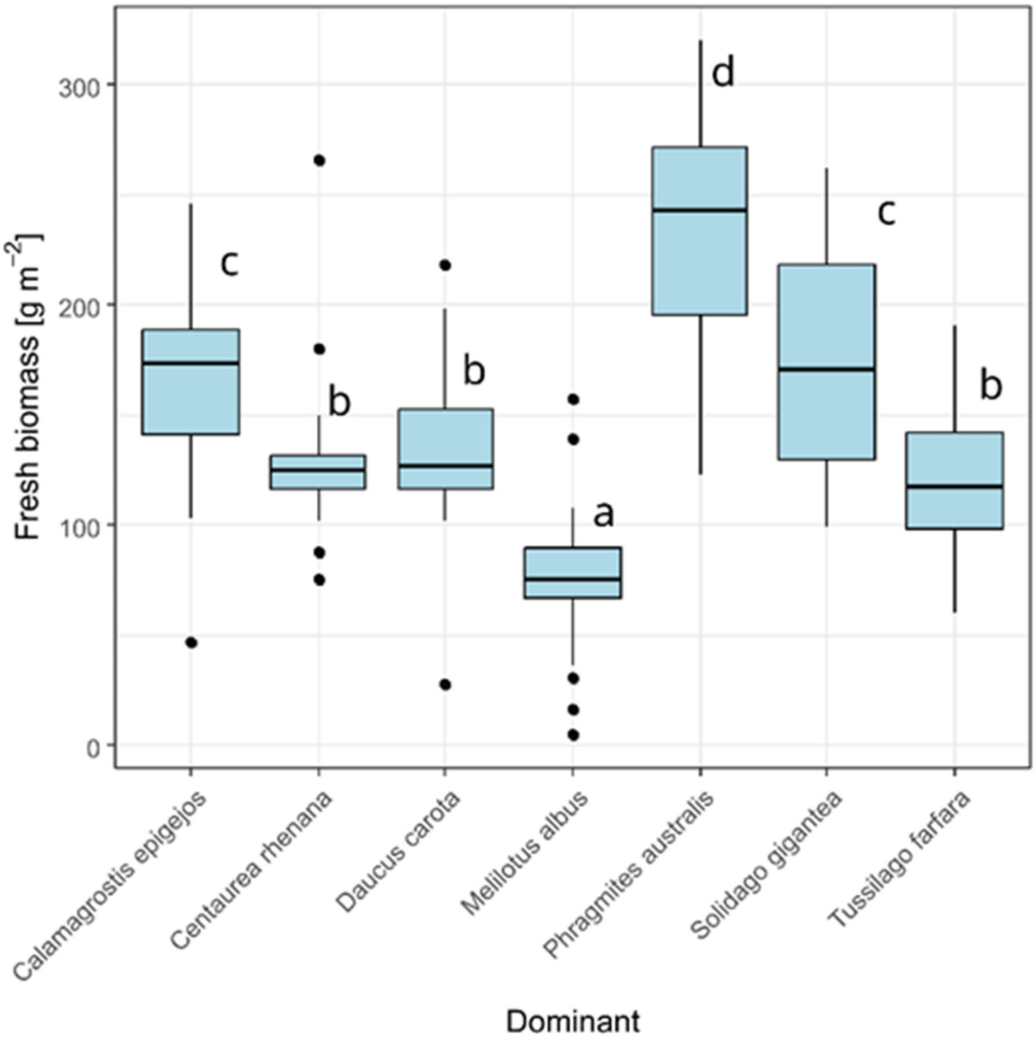


Figure 3. Variation in fresh aboveground biomass among vegetation patches dominated by different plant species. Boxplots show the median (horizontal line), interquartile range (box), values within 1.5 × IQR (whiskers), and outliers (points). Different letters indicate significant differences between dominant species according to the Kruskal–Wallis test followed by Dunn's post hoc test (Benjamini–Hochberg correction, $p < 0.05$).

According to Dunn's post hoc test, *Phragmites australis* formed a separate statistical group, indicating significantly greater biomass (median = 243.0 g per 0.25 m^2) than all other dominant species. In contrast, *Melilotus albus* exhibited significantly lower biomass (median = 74.9 g per 0.25 m^2). Stands dominated by *Calamagrostis epigejos* and *Solidago*

gigantea had similar values and were characterised by relatively high biomass. Intermediate biomass values were observed in communities dominated by *Centaurea rhenana*, *Daucus carota* and *Tussilago farfara*.

The boxplot distribution further indicated substantial variability within some dominant species, particularly *Solidago gigantea* and *Phragmites australis*, whereas biomass values associated with *Centaurea rhenana* showed comparatively lower dispersion.

Principal component analysis revealed clear multivariate differentiation among vegetation patches associated with dominant plant species (Figure 4). The first principal component (PC1) explained 23.8% of the total variance, whereas the second component (PC2) accounted for 7.2%, together explaining approximately 31% of the variation observed in the dataset.

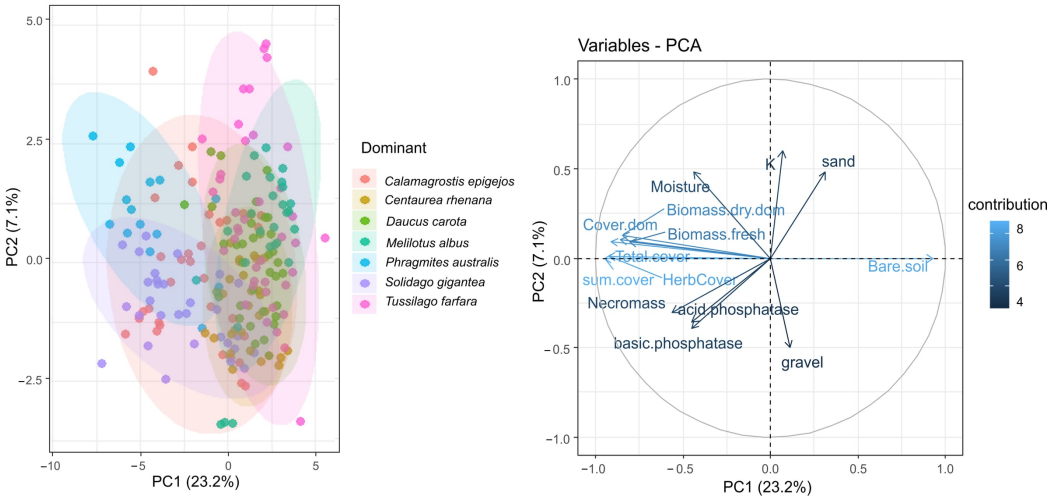


Figure 4. Principal component analysis (PCA) of the environment, soil, and biological variables. (**Left**) Distribution of sampling plots in the space defined by the first two principal components, coloured according to dominant plant species. (**Right**) PCA loadings showing the contribution and direction of individual variables. Arrow length indicates the strength of the relationship with the ordination axes, while the angle between vectors reflects the degree of correlation among variables. Variables pointing in similar directions are positively correlated, whereas variables pointing in opposite directions are negatively correlated.

Several environmental gradients contributed strongly to sample differentiation along PC1. Bare soil cover was positively associated with PC1, while vegetation cover variables (Cover.dom. HerbCover and total vegetation cover) were negatively associated with this axis. Particle-size fractions, particularly sand and gravel, contributed to sample separation along both PCA dimensions. Soil moisture showed a strong association with the upper portion of the ordination space, indicating an important moisture gradient underlying vegetation differentiation.

The ordination of plots showed partial overlap among dominant species, suggesting that vegetation types shared some environmental characteristics. Nevertheless, communities dominated by *Phragmites australis* tended to occupy a distinct region of the ordination space associated with higher moisture conditions, whereas patches dominated by ruderal and grassland species were more widely distributed along the environmental gradient represented by PC1.

The Spearman correlation heatmap indicated a complex network of relationships among vegetation, soil and biological variables (Figure 5). Both positive and negative significant associations were detected, whereas non-significant correlations were omitted from the visualization.

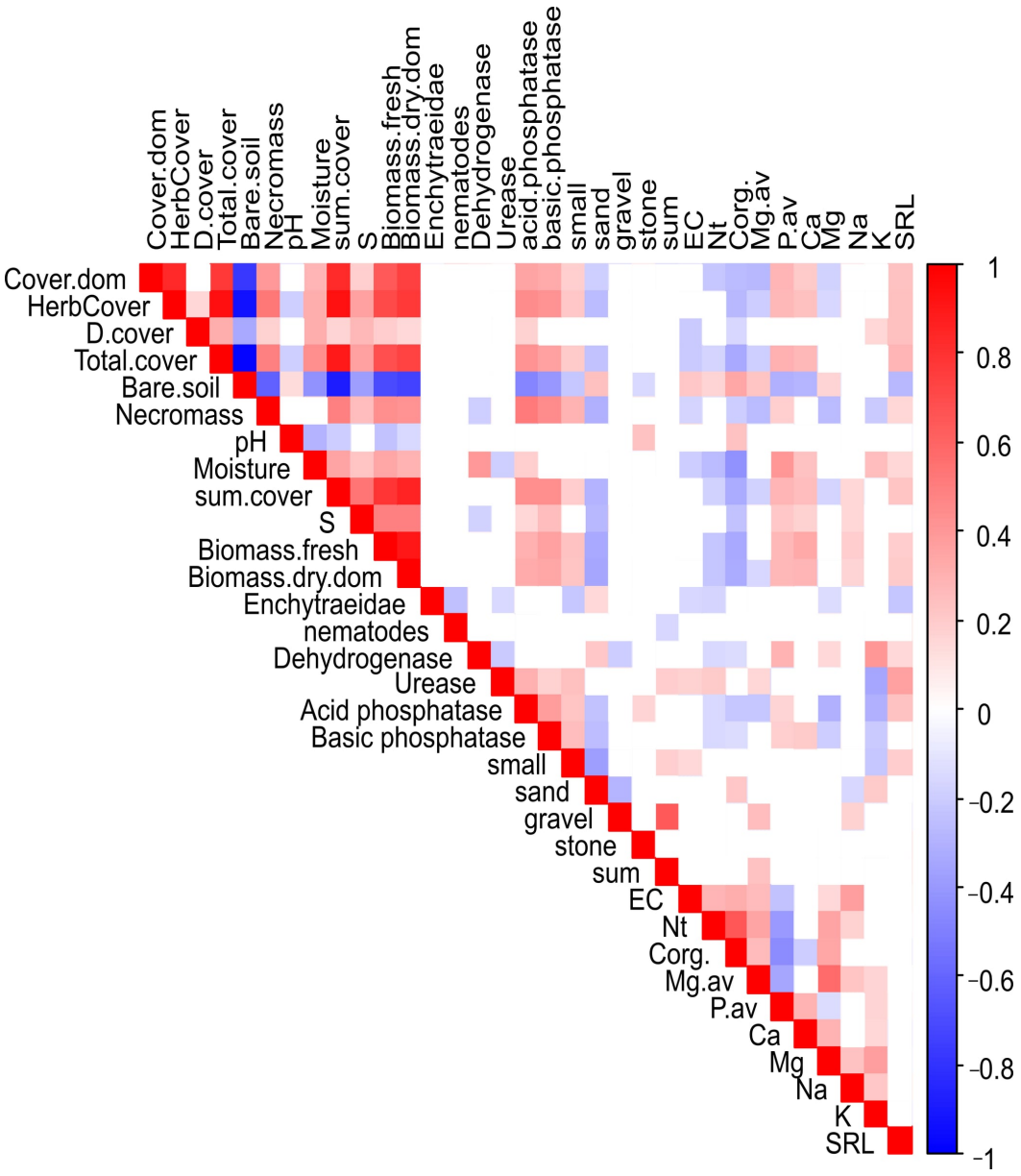


Figure 5. Significant Spearman rank correlations (r_s $p < 0.05$) between fresh biomass and environmental, soil, and biological variables. Colour intensity indicates the magnitude of the correlation coefficient, with blue indicating negative correlations and red indicating positive correlations. Darker shades correspond to stronger relationships. White (blank) cells indicate correlations that were not statistically significant ($p \geq 0.05$).

Strong positive correlations occurred among several vegetation-related parameters. While negative relationships were mainly observed between variables representing contrasting habitat conditions. s.

Variation partitioning demonstrated that soil physicochemical properties explained a substantially larger proportion of variation in vegetation structure and productivity than biological factors (Figure 6). The unique contribution of soil physicochemical variables accounted for 29.4% of the explained variance, whereas biological variables independently explained only 2.3%. A further 16.3% of variance was jointly explained by both groups of predictors, indicating considerable overlap between abiotic and biotic influences. The unexplained fraction remained relatively high (51.9%).

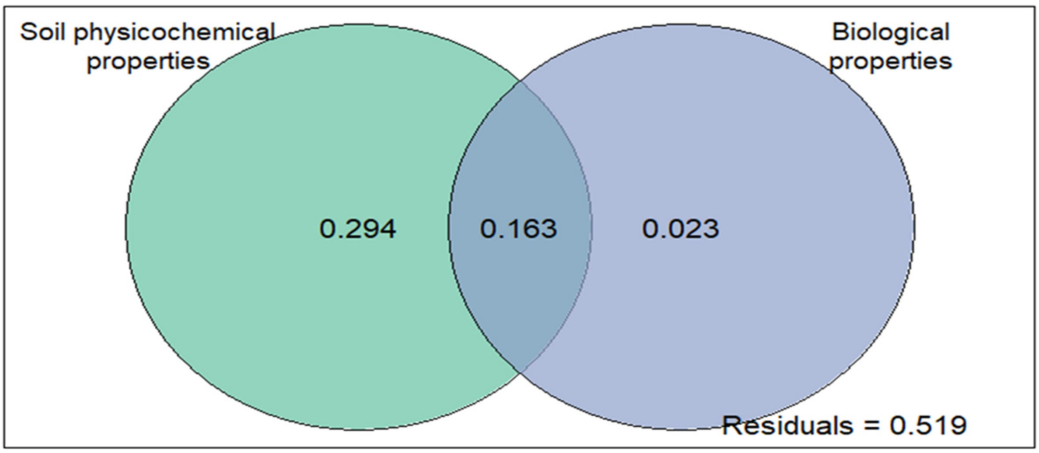


Figure 6. Venn's diagram showing variation partitioning of vegetation structure and productivity variables (species cover, species richness, fresh biomass) between two groups of explanatory variables: soil physicochemical properties and biological properties.

Permutation tests confirmed the significance of both predictor groups. Soil physicochemical properties exerted the strongest effect on vegetation characteristics (Pseudo-F = 7.971, $p = 0.001$), whereas biological variables also had a significant but weaker influence (Pseudo-F = 2.915, $p = 0.005$).

Overall, these results suggest that vegetation structure, productivity and species richness in the studied habitats are primarily controlled by abiotic soil conditions, while biological processes provide an additional, though comparatively smaller, contribution to observed patterns.

3.2. The Biomass Amount and Its Energy Potential of the Studied Species

The energy potential of vegetation naturally occurring on mineral substrates in post-mining areas depends on two main factors: the amount of dry biomass produced per unit area and its calorific value. Therefore, the assessment of these plant species should consider not only their capacity to accumulate biomass but also the amount of energy that can theoretically be obtained from this biomass. The results presented in Table 2 demonstrate differences in biomass productivity and estimated energy potential among the investigated species, indicating that their contribution to potential bioenergy production is not uniform.

Phragmites australis exhibited the highest dry biomass yield among the investigated species, reaching 7.50 t/ha, with an estimated net calorific value (NCV) of 16.6–18.1 MJ/kg. Consequently, its theoretical energy potential was estimated at 124–136 GJ/ha, making it the most promising species in terms of energy yield per unit area among those examined. The relatively high biomass production, combined with a suitable calorific value, suggests that this species could be considered a potential feedstock for bioenergy applications, provided that harvesting, moisture content, ash composition, and contaminant concentrations are acceptable for the intended conversion technology.

Calamagrostis epigejos produced 4.47 t/ha of dry biomass and had an estimated calorific value of approximately 17.9 MJ/kg, corresponding to a theoretical energy potential of about 80 GJ/ha. Solidago gigantea yielded 5.04 t/ha, with a calorific value of approximately 17.2 MJ/kg and a theoretical energy potential of 86.6 GJ/ha. These results indicate that both species may also represent potential sources of bioenergy. Although their biomass yields were lower than that of *Phragmites australis*, their estimated calorific values remained within a range that may be suitable for thermochemical energy conversion.

Table 2. Calorific value of biomass from plant species naturally occurring on mineral substrates in post-mining areas.

Species Name	Mean Dry Biomass g/0.25 m^2	Biomass per g/1 m^2	Participation in the Total Biomass g/kg/‰	Energy Potential MJ/kg s.m.	Dry Biomass. t/ha	Estimated Calorific Value of Dry Matter (NCV) MJ/kg	Theoretical Energy Potential GJ/ha
Phragmites australis	187.4	749.6	244.6	16.6–18.1	7.50	16.6–18.1	124–136
Calamagrostis epigejos	111.7	446.8	145.8	17.0–17.5	4.47	17.9	80
Solidago gigantea	125.9	503.6	164.3	17.9	5.04	17.2	86.6
Centaurea rhenana	97.2	388.8	126.8	17.1	3.89	16–18	62–70
Daucus carota	94.7	378.8	123.6	16.1	3.79	16	61
Tussilago farfara	77.9	311.6	101.7	16–18	3.12	16–18	50–56
Melilotus albus	71.5	286.0	93.3	16–18	2.86	17.1	49

The remaining species (*Centaurea rhenana, Daucus carota, Tussilago farfara, and Melilotus albus*) showed lower dry biomass yields, ranging from 2.86 to 3.89 t/ha. Their estimated theoretical energy potentials were approximately 49–70 GJ/ha, depending on the species and the calorific value assumed. Thus, these plants cannot be excluded as potential bioenergy resources solely on the basis of their calorific values. However, their lower biomass yields result in lower energy production per unit area compared with the three leading species. Their practical suitability would therefore depend on the feasibility of biomass collection, the availability of sufficient quantities, and the costs associated with harvesting, transport, and processing.

The comparison also highlights the importance of distinguishing between the calorific value of biomass and its overall energy potential per hectare. A relatively high calorific value does not necessarily result in the highest energy yield per unit area, because the latter also depends on biomass productivity. In this study, Phragmites australis combines the highest biomass yield with a suitable calorific value, resulting in the highest estimated theoretical energy potential. The other species may contribute to bioenergy production where they occur in sufficient quantities or can be collected together with other vegetation. Nevertheless, their contribution should be assessed in relation to the composition and availability of the local plant community rather than calorific value alone.

Importantly, the energy values presented in Table 2 represent theoretical estimates rather than measured recoverable energy. Actual energy output will depend on biomass moisture content at harvesting, seasonal variation, ash content, combustion or conversion efficiency, and the energy required for collection and pretreatment. Furthermore, because the plants grow on post-mining mineral substrates, their suitability for energy applications should not be determined by calorific value alone. The potential accumulation of potentially toxic elements and other contaminants must be assessed before the biomass is used as a fuel, particularly where combustion could concentrate contaminants in ash or release them into flue gases. Depending on the results of such assessments, some biomass may be suitable for energy recovery, whereas other material may require alternative management or controlled disposal.

Overall, the findings indicate that naturally occurring vegetation in post-mining areas may represent a supplementary biomass resource, with Phragmites australis, Calamagrostis epigejos, and Solidago gigantea showing the highest theoretical energy potential per unit area among the investigated species. However, not all species should automatically be considered equally suitable for energy production. Their selection requires an integrated assessment of biomass yield, calorific value, fuel properties, contaminant concentrations, harvesting feasibility, and the environmental safety of the selected conversion route. This approach would help determine whether energy recovery is technically feasible and environmentally appropriate while supporting the potential use of vegetation from post-mining landscapes as a locally available renewable resource.

3.3. Remote Sensing-Based Group Analysis

The monthly mean time series show the NDVI (Figure 7) and NDMI (Figure 8) courses over the analysed period, from March 2016 to August 2026. *Solidago gigantea* dominated vegetation patches with both the highest average NDVI and NDMI values. This indicates a consistently green and dense canopy. This is consistent with the field and biomass analysis, as this group has among the highest biomass values. *Phragmites australis*-dominated vegetation patches have the highest monthly peak NDVI and the second-highest average NDMI, suggesting a dense, productive canopy with favourable moisture conditions. However, the course also shows high seasonal amplitudes. *Calamagrostis epigejos* has a lower mean NDVI than *Solidago gigantea* and *Phragmites australis*-dominated vegetation patches, but its average monthly peak NDVI is comparatively high, suggesting a clear seasonal canopy maximum with lower values outside the peak growing period. The course of *Centaurea rhenana*-dominated vegetation patches is characterised by moderate NDVI values with the lowest NDMI, suggesting a relatively short period of favourable conditions. *Tussilago farfara*-dominated vegetation plots have the lowest long-term mean NDVI. However, their average monthly peak can still be high. This implies strong seasonality: the vegetation can reach a pronounced maximum but remain relatively low throughout the annual cycle. *Daucus carota*-dominated vegetation patches have a moderate average NDVI and a relatively positive mean NDMI. Its average monthly peak NDMI was the highest among the summaries. *Melilotus albus* shows intermediate NDVI and relatively low mean NDMI.

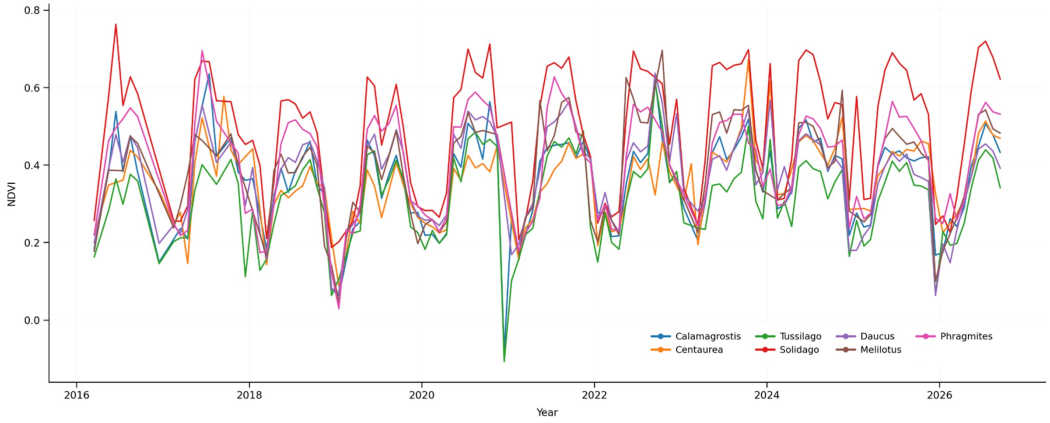


Figure 7. Monthly mean NDVI course by vegetation group.

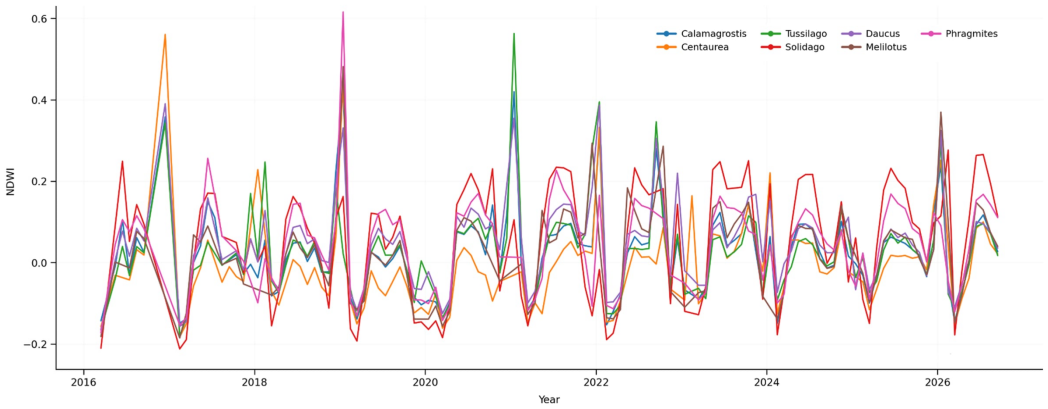


Figure 8. Monthly mean NDMI course by vegetation group.

The model was calibrated using field-measured total dry biomass and corresponding Sentinel-2 predictors from 2016. The calibrated relationship was subsequently applied to yearly Sentinel-2 predictor sets for 2017–2026 to generate model-based biomass estimates. Because no independent biomass measurements were available after 2016, the reconstructed values for 2017–2026 could not be validated against field observations (Figure 9). They should therefore be interpreted as satellite-based model estimates rather than as measured biomass values. Table 3 presents the number of calibration observations and group-wise leave-one-point-out cross-validation statistics, including R^2, MAE, RMSE, and prediction bias. Overall, the model performed decently, having an R^2 of 0.668, with an MAE of 16.31 g/0.25 m^2 and an RMSE of 23.44 g/0.25 m^2; however, the performance differed substantially between groups, with *Calamagrostis epigejos*, *Solidago gigantea* and *Tussilago farfara* having a relatively high R^2 of 0.75, 0.61, and 0.58 respectively. *Centaurea's* biomass is predicted poorly, having an R^2 of 0.244. The remaining vegetation groups, *Daucus carota*, *Melilotus albus*, and *Phragmites australis* were estimated with negative R^2, indicated that the pooled predictions did not reliably reproduce within-group variation for these groups.

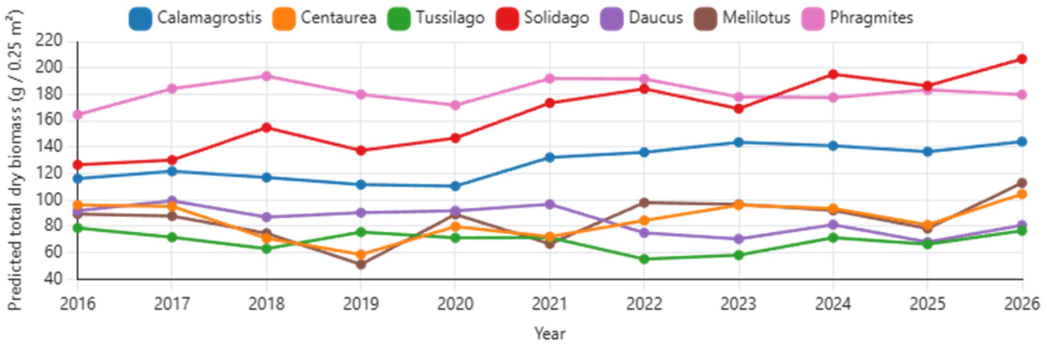


Figure 9. Exploratory model-based reconstruction of annual total dry biomass by vegetation group.

A point-level bootstrap with 1000 replicates was used to assess the sensitivity of the reconstructed group-year means to calibration-sample composition and model refitting. The complete preprocessing and Ridge-regression pipeline was refitted in each replicate. The intervals were generally narrowest in 2016 and wider in subsequent years, indicating greater uncertainty when the model was transferred beyond the calibration year. Particularly broad intervals were obtained for *Solidago gigantea*, *Phragmites australis*, and *Melilotus albus*.

Table 3. Group-wise performance of the pooled Ridge biomass model evaluated using leave-one-point-out cross-validation.

Vegetation Group	Group Size	CV R^2	MAE. (g/0.25 m^2)	RMSE. (g/0.25 m^2)	Mean Annual Biomass (g/0.25 m^2)	Mean Biomass Interval Width, (g/0.25 m^2)
Together	146	0.668	16.31	23.44	-	-
Calamagrostis epigejos	21	0.754	12.87	15.29	122.77	48.78
Solidago gigantea	30	0.611	16.66	20.31	147.97	49.77
Tussilago farfara	32	0.580	9.79	12.72	74.59	30.48
Centaurea rhenana	26	0.244	11.95	22.59	92.32	107.38
Daucus carota	21	−0.047	14.40	19.40	88.32	31.16
Melilotus albus	6	−0.533	43.83	46.04	90.45	59.35
Phragmites australis	10	−0.173	41.63	50.99	169.51	75.19

However, this agreement does not constitute independent validation because those spectral variables contributed directly to model fitting. Moreover, spontaneous succession may alter species composition, dominance, canopy structure, phenology, and biomass allocation, potentially changing the relationship between spectral response and dry biomass. Accordingly, the 2017–2026 trajectories should be interpreted as exploratory reconstructions under the assumption that the relationship calibrated in 2016 remained approximately applicable.

Model-estimated dry biomass was subsequently combined with group-specific calorific values to calculate theoretical energy potential. Table 4 summarizes mean model-estimated biomass for 2016–2026 and the corresponding energy estimates for each vegetation group.

Table 4. Group-level summary of model-estimated total dry biomass and theoretical energy potential for 2016–2026.

Group	Mean of Annual Total Dry Biomass Estimates (g/0.25 m^2)	Range of Annual Model-Estimated Total Dry Biomass (g/0.25 m^2)	Mean Energy (GJ/ha)	Estimated Energy Range (GJ/ha)
Phragmites australis	181.53	164.62–193.76	125.98	109.31–140.29
Solidago gigantea	164.65	126.66–206.82	113.28	87.14–142.29
Calamagrostis epigejos	128.27	110.49–144.18	91.84	79.11–103.33
Melilotus albus	85.19	51.19–112.90	57.93	32.76–81.29
Daucus carota	84.84	68.14–99.41	54.64	43.88–64.02
Centaurea rhenana	84.81	58.69–104.48	58.01	40.14–71.46
Tussilago farfara	69.13	55.27–78.82	47.01	35.37–56.75

Phragmites australis had the highest central estimate of theoretical energy potential, primarily because of its high estimated biomass. Nevertheless, this result was associated with a small calibration sample, broad bootstrap intervals, negative within-group cross-validated R^2, and substantial prediction bias. Its apparent energetic advantage should therefore be regarded as an exploratory scenario rather than a robust ranking. *Solidago gigantea* had the second-highest mean annual median estimate, approximately 113.28 GJ/ha, and displayed the clearest increase in its central reconstructed trajectory. However, its

bootstrap intervals widened markedly in later years, indicating that the magnitude of the inferred increase was highly sensitive to the calibration sample.

Calamagrostis epigejos had an intermediate mean annual energy estimate of approximately 91.84 GJ/ha. Its reconstruction was comparatively better supported by group-wise cross-validation, although the overlapping bootstrap intervals did not provide strong evidence of a consistent temporal increase. The remaining groups had lower central estimates, approximately 47.01–58.01 GJ/ha. Differences among *Centaurea stoebe*, *Melilotus albus*, and *Daucus carota* were small relative to their uncertainty and should not be interpreted as a definitive ranking. The *Melilotus* estimates are particularly uncertain because the group was represented by only six calibration observations and showed negative group-wise predictive performance.

Overall, differences in theoretical energy potential were driven mainly by differences in model-estimated dry biomass, while variation in calorific value had a secondary influence. The energy estimates inherit all limitations of the biomass reconstruction, including the absence of independent field validation after 2016. They represent gross theoretical energy content and do not account for harvesting losses, retained biomass, moisture at use, ash content, processing requirements, or conversion efficiency.

4. Discussion

4.1. The Potential Double Role of Mineral Habitats Post-Mining Sites

Mineral post-mining habitats arise directly from the exploitation of energy resources, primarily hard coal. They thus constitute an integral—albeit often treated as a byproduct—element of the raw material extraction process. Extraction leads to the displacement of mineral geological material and the removal of the original soil cover, and the creation of spoil heaps and other landforms resulting from human mining activity [28]. The mineral substrates formed through mining activity typically exhibit physical and chemical properties distinct from natural soils or substrates; these characteristics include, among others, low organic matter content, limited nutrient availability, high variability in moisture, temperature, particle-size distribution, and a mosaic-like distribution of microhabitats. Such conditions create a strong environmental filter that selects for species and functional strategies capable of colonising high-stress habitats [29].

At the same time, the end of mining operations does not mean the end of biological processes, including biomass formation. Pioneer organisms spontaneously colonise mineral substrates, which organise into vegetation patches that constitute elements of a developing ecosystem (novel ecosystem), as a result of spontaneous succession. Studies of post-mining areas indicate that spontaneous succession can lead to the gradual development of increasingly complex plant communities under Central European conditions, even to the formation of late-stage forests within a hundred years. In this sense, the mineral substrates of post-mining habitats undergo a transformation from an almost entirely mineral substrate to a functioning ecosystem, in which vegetation of non-analogous species composition becomes one of the main factors shaping the further development of the environment [30].

The spontaneous production of plant biomass is of particular importance. Biomass represents not only the result of primary production but also the fundamental mechanism by which organic matter enters a developing ecosystem. The production of roots, leaves, shoots, and other plant organs increases the input of organic carbon into the substrate, subsequently providing a substrate for microorganisms and soil organisms. As succession progresses, increased organic matter production can lead to the development of an organic layer, changes in the substrate's surface structure, and enhanced biological activity. Studies on post-mining sites have shown that over time, carbon flux into the trophic network and

the biomass of soil organisms increase, accompanied by changes in the structure of the food web [6].

While species such as *Phragmites australis*, *Calamagrostis epigejos*, and *Solidago gigantea* demonstrated substantial dry biomass accumulation and high theoretical energy yields (e.g., 80–136 GJ/ha), a high energy yield does not automatically translate to immediate technical readiness for thermochemical conversion. Herbaceous biomass generally exhibits higher ash content, volatile matter, and concentrations of alkali metals (K, Na), chlorine, and sulfur compared to traditional woody fuels. When grown on heterogeneous post-mining residues and coal dumps, vegetation may additionally assimilate inorganic trace elements or heavy metals. These chemical features can influence thermal behavior, potentially contributing to ash slagging, fouling on heat-transfer surfaces, high-temperature corrosion, or requiring specific emission controls during direct combustion. Consequently, the metrics reported here represent a primary ecological-energetic screening, and future research should incorporate detailed proximate/ultimate fuel analyses, ash melting behavior, and leaching studies to fully characterize commercial energy conversion pathways.

Notwithstanding these theoretical and compositional considerations, practical experience and field observations in rehabilitated post-mining landscapes present encouraging perspectives. Despite the environmental heterogeneity of coal dump substrates, practical applications demonstrate that the thermochemical utilization of such biomass (e.g., via localized heat generation or co-firing) consistently operates within environmentally permissible emission standards. Crucially, multi-year monitoring indicates that natural phytocenotic succession leads to the progressive self-stabilization of the local ecological situation within a few years. The establishment of stable plant communities naturally improves soil structure, mitigates wind and water erosion, and promotes the phytostabilization of trace elements within the root system—thereby enhancing overall environmental safety while simultaneously providing a sustainable bioenergy resource.

Vegetation is, therefore, not merely a passive recipient of habitat conditions. During succession, it acts as an ecosystem engineer, modifying the properties of the mineral substrate through biomass production, litter accumulation, root system development, and microclimate alteration. Interestingly, the impact of plants on the environment may be linked not only to their presence but also to their functional traits. Studies of spontaneously developing post-mining habitats have shown that plant functional traits can explain the variation in soil chemical and biological properties more effectively than simple classifications of vegetation patch types. Furthermore, vegetation cover and litter input were positively associated with the abundance of numerous soil fauna groups.

In this context, biomass should be analysed not only quantitatively but also qualitatively. The same amount of biomass can have different implications for ecosystem functioning depending on its structure, chemical composition, tissue durability, and allocation patterns among plant organs. Traits such as specific leaf area (SLA), leaf dry matter content (LDMC), plant height, root biomass fraction, root-to-shoot ratio, leaf nitrogen content, and root system characteristics inform strategies for resource use and stress tolerance. In the mineral-rich substrates of post-mining sites, these traits may reflect a trade-off between rapid growth and resilience to water or nutrient deficits, high temperatures, or potentially toxic elements.

The annual biomass series must be interpreted in the context of temporal model transfer. Field biomass was measured only in 2016, and the calibrated relationship was subsequently applied to Sentinel-2 predictors from 2017 to 2026 without independent field validation. This approach assumes approximate temporal stability in the relationships among spectral indices, vegetation cover, vegetation-group identity, and total dry biomass. Such stability cannot be assumed fully in habitats undergoing spontaneous succession. Changes in species composition, dominance, canopy height, leaf area, phenology, leaf-to-stem allocation, and

the proportion of standing dead material could alter spectral responses independently of dry biomass. Consequently, the reconstructed series represents the biomass values expected under the 2016-calibrated relationship, rather than direct evidence of actual annual biomass production. Even for the better-performing groups, apparent temporal changes require confirmation through repeated biomass and vegetation-composition surveys. Even for the better-performing groups, apparent temporal changes require confirmation through repeated biomass and vegetation-composition surveys.

The remote-sensing reconstruction showed the most reliable within-group performance for *Calamagrostis epigejos*, *Solidago gigantea*, and *Tussilago farfara*. For these groups, cross-validated R^2 values were 0.754, 0.611, and 0.580, respectively, indicating that the model captured a substantial component of biomass variation. The comparatively strong performance for *Calamagrostis epigejos* and *Solidago gigantea* is consistent with their distinct canopy development and relatively high vegetation cover. The lower prediction errors for *Tussilago farfara* suggest that its biomass was estimated with reasonable absolute accuracy, although its lower biomass range should be considered when comparing error magnitudes among groups. Model performance was substantially weaker for the remaining vegetation groups. The group-wise cross-validated R^2 was low for *Centaurea rhenana* and negative for *Daucus carota*, *Melilotus albus* and *Phragmites australis*. A negative cross-validated R^2 indicates that, within the corresponding group, predictions were less accurate than predictions based on the observed group mean. The reconstructed temporal courses for these groups should therefore be treated as exploratory and not definite. This limitation is particularly important for *Melilotus albus* and *Phragmites australis*, which were represented by relatively small calibration samples. Furthermore, field biomass measurements were available only for the 2016 calibration year. Biomass values for 2017–2026 were obtained by applying the 2016-calibrated relationship to the corresponding annual Sentinel-2 predictors. Because no independent field measurements were available for the subsequent years, these values represent unvalidated model-based reconstructions rather than observed annual biomass. Their interpretation assumes that the relationship between biomass and spectral characteristics remained sufficiently stable over time.

Annual theoretical energy potential was calculated from model-estimated dry biomass and therefore inherits all uncertainties associated with temporal model transfer. The estimates for 2017–2026 should be interpreted as exploratory energy scenarios under the assumption that the 2016-calibrated biomass–spectral relationship remained applicable. They do not represent validated annual energy yields. This qualification is particularly important for vegetation groups with weak or negative group-wise cross-validated performance.

The estimated theoretical energy potential largely reflected differences in model-estimated dry biomass, because variation in biomass yield was greater than variation in group-specific calorific values. *Phragmites australis* and *Solidago gigantea* produced the highest calculated mean energy potentials, followed by *Calamagrostis epigejos*. The remaining groups had considerably lower estimated values. These differences indicate that biomass quantity was the principal determinant of area-based energy potential, while calorific value modified the theoretical energy potential to a lesser extent.

In this approach, the main research challenge is to determine the balance point between leaving biomass as part of natural capital and sustainably acquiring it as a local energy resource. Answering this question requires a simultaneous assessment of biomass production and its energy value, carbon content, and its impact on the mineral substrate's properties, biodiversity, and ecosystem functions and services. This perspective can create the basis for a transition from the classic reclamation of post-mining areas to the management of the dynamic natural potential of spontaneously developing new ecosystems.

4.2. The Phragmites Australis Biomass

Regarding the above-ground biomass of common reed (*Phragmites australis*) harvested from a 0.25 m^2 area growing on mineral material at post-mining sites, the difference between fresh biomass and dry biomass is substantial. It depends primarily on the timing of the harvest and habitat moisture levels. Studies on *Phragmites australis* show a dry matter content of approximately 40–45% of the fresh biomass. For instance, one study reported a dry matter content of 44.9%, while another found an average of 42.68%. Dry biomass constitutes about 40–45% of fresh biomass, while the FW–DW difference amounts to approximately 55–60% of the fresh mass.

If 1 kg of fresh *Phragmites australis* was harvested from your 0.25 m^2 plot, the expected dry biomass is approximately 0.43 kg, representing a difference of about 0.57 kg of water. However, it is worth noting that these values can be significantly higher in dense reed beds. Field studies showed an average fresh biomass of approximately 1566 g/m^2 and a dry biomass of approximately 532 g/m^2; for a 0.25 m^2 area, this corresponds to 392 g FW and 133 g DW, respectively [31,32].

4.3. The Calamagrostis Epigejos Biomas

For the small-reed (*Calamagrostis epigejos*), more specific estimates are available. There are studies that used exactly 0.25 m^2 plots—and the plants dried for three weeks. The average mass was for the fresh biomass 41 g/0.25 m^2, and for dry biomass: 34 g/0.25 m^2; difference: 7 g/0.25 m^2; dry mass constituted approximately 82.9% of the fresh mass. A water content of 17% is relatively low for green biomass and likely stems from the specific nature of the material and the timing of sample collection. Therefore, the 7 g figure might not be the universal difference applicable to every stand of this grass [33].

Other studies on *C. epigejos* demonstrate significant variability in biomass depending on the habitat. Grüttner and Heinze [34] recorded 300–1500 g of above-ground dry biomass per m^2 across various habitats. For an area of 0.25 m^2, this would imply a range of approximately 75–375 g of dry biomass/0.25 m^2. Studies on the expansion of *C. epigejos* have also shown significant amounts of above-ground biomass, depending on habitat conditions and nitrogen availability.

4.4. The Biomass Relationships to the Biotic Conditions of Mineral Habitats

The extraordinary poor, oligotrophic, mineral habitat conditions of novel ecosystems on coal mine heaps cannot be returned to the historic state, i.e., the previous pre-mining state [35]. Moreover, the poor, oligotrophic, mineral habitat conditions represent the most rare and intensively decreasing habitats in urban industry landscapes [36–38]. Primary succession is a rare phenomenon that can be observed. In the early stages of succession, soil (or soil substrate) on the post mining sites the organisms may depend on a specific combination of plant species biochemical characteristics [39–41]. Apart from the complexity of primary producer plant combinations, the microbial assemblages, the specific abiotic conditions, and the limited understanding of these relationships in natural and semi-natural ecosystems, human industrial activity brings a completely new set of challenges [42,43].

4.5. Plant Species Composition Diversity and the Amount of Biomass

Many studies conducted in natural and semi-natural ecosystems have shown positive relationships between biodiversity indices and biomass. The unimodal (hump-shaped) distribution reflects the relationship between biomass amount and vegetation plant species composition (alpha and beta diversity) [44,45].

Many studies in this field are experimental (not conducted in the field) research. The artificially simplified factors and the explanations for the positive relationship between

biodiversity and biomass amount are examined and obtained. The selection effect assumes that the more diverse the community and the ecosystem, the more dependent they are on the productivity of the species that build the community [41].

Sampling effects do not fully explain how biodiversity influences biomass. The sampling effects occur far less generally than previously suspected. The merging of sampling, complementarity, and facilitative effects, which are mutually non-exclusive, is the most explicable. The field studies, which focused on the relationship between vegetation species composition diversity and above-ground biomass, included comparisons of tree species composition across three different forest types [44,46,47].

Research conducted across hundreds of post-coal mine heaps has revealed that herbaceous spontaneous vegetation types can be characterised by the abundant presence of a single dominant species, often accompanied by single individuals of numerous other species. The mineral post-black coal mining sites provide a stony gravel soil substrate for the colonising organisms [48–53].

5. Conclusions

The results demonstrate that spontaneously produced biomass should be considered not only a structural component of vegetation developing on mineral post-mining substrates, but also a potential natural and energy resource generated within novel ecosystems. Because vegetation develops under environmental conditions substantially different from those of natural, semi-natural and intensively managed ecosystems, biomass characteristics and potential should be assessed in relation to habitat conditions, vegetation structure and ecosystem development rather than biomass quantity alone.

Biomass amount varied among species composition of spontaneously developing vegetation types and was associated with selected components of vegetation structure and diversity. This indicates that biomass accumulation may be controlled differently by dominant and subordinate vegetation components, and that species diversity alone cannot serve as a universal predictor of biomass production. Relationships between biomass and substrate properties further suggest that biomass synthesis on mineral post-mining habitats is shaped by specific environmental filtering and resource limitations rather than simply by increasing organic matter content.

Greater biomass accumulation may contribute to biological activity and carbon fluxes, representing an important pathway through which mineral substrates become incorporated into biological carbon cycling. Biomass should therefore be regarded both as a product of ecosystem development and as a potential driver of ecosystem functioning.

From an energy perspective, biomass quantity should be distinguished from biomass quality. Its potential value as a renewable resource depends on species composition, biomass characteristics, moisture content, productivity and habitat conditions. Assessment for bioenergy applications should therefore integrate ecological parameters with dry matter production, calorific value, energy yield and carbon balance.

The coexistence of spontaneous ecosystem development and energy and resource production creates a management challenge. Biomass harvesting could utilise a renewable resource generated without conventional agricultural production, but excessive removal may interfere with succession, carbon accumulation and habitat development. Its utilisation should consequently be evaluated within an ecosystem-based framework balancing energy potential with ecological functions.

Future research should address long-term changes in biomass quantity and quality, functional traits, calorific value, carbon content, energy yield and decomposition during post-mining succession. Particular attention should be given to different carbon pools and to the distinction between newly incorporated organic matter, decomposed material and

more stable carbon fractions. Overall, spontaneously synthesised biomass represents a multifunctional resource that links ecosystem development, carbon cycling, vegetation functioning, and potential renewable energy production, while offering management opportunities that balance biodiversity, ecosystem functioning, carbon sequestration, and sustainable resource utilisation.

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