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Natural and Managed Grasslands Productivity during Multiyear in Ex-Arable Lands (in the Context of Climate Change)

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Abstract: Ex-arable land-use change is a global issue with significant implications for climate change and impact for phytocenosis productivity and soil quality. In temperate humid grassland, we examined the impact of climate variability and changes of soil properties on 23 years of grass productivity after conversion of ex-arable soil to abandoned land (AL), unfertilized, and fertilized managed grassland (MG_{unfert} and MG_{fert}, respectively). This study aimed to investigate the changes between phytocenosis dry matter (DM) yield and rainfall amount in May–June and changes of organic carbon (C_{org}) stocks in soil. It was found that from 1995 to 2019, rainfall in May–June tended to decrease. The more resistant to rainfall variation were plants recovered in AL. The average DM yield of MG_{fert} was 3.0 times higher compared to that in the AL. The DM yields of AL and MG were also influenced by the long-term change of soil properties. Our results showed that C_{org} sequestration in AL was faster (0.455 Mg ha⁻¹ year⁻¹) than that in MG_{fert} (0.321 Mg ha⁻¹ year⁻¹). These studies will be important in *Arenosol* for selecting the method for transforming low-productivity arable land into MG.

Keywords: land use; rainfall; soil properties; C_{org} stocks; *Arenosol*



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1. Introduction

Perennial grasses are often used to stop the degradation of arable sandy soils in Europe [1–3]. Their aboveground biomass is used for animal feed production, and the root system and fallen plant material promote organic carbon (C_{org}) sequestration in soil [4]. Particularly low-yielding arable soils may be abandoned. In such areas, cenoses of natural grasses formed over several years are less productive due to insufficient amount of nutrients in soil but perform other important functions in the ecosystem: they help to preserve plant diversity, water reserves in soil, inhibit soil erosion, and reduce CO₂ emissions [5,6]. The conversion of arable lands to abandoned ones does not require material costs; however, it is socially sensitive due to the cessation of agricultural activities.

After cessation of agricultural activities, abandoned lands restore soil fertility, and repeated return to traditional agriculture after some time can increase the yield potential and increase soil C_{org} sequestration at the same time [7]. Globally, land abandonment is one way of capturing carbon, conserving natural biodiversity, creating buffer zones, and isolating areas with damaged biogeochemical cycles [8]. On the other hand, however, it remains relevant to find a compromise between agricultural activity and environmental stability [9,10], as global demand for food continues to grow [11,12]. Conversion of arable lands to grassy phytocenoses promotes C_{org} accumulation; however, the rate of accumulation depends on the number and type of species of herbaceous vegetation [13]. Grassland formed from managed grasses accumulates C_{org} faster compared to those formed from natural vegetation [4].

Accumulation takes place more intensely when several species of grasses are grown, and the ratio of grass species is important for the preservation of carbon stocks in grassland soil [14]. In addition, managed grasses allow the formation of more valuable and less weedy grassland compared to the natural vegetation that is formed from the seeds of various plants present in soil, although both ways can be effective in terms of nature conservation [3]. C_{org} accumulation in topsoil (A horizon) is also significantly influenced by soil texture, which determines its sorption capacity to accumulate organic matter [15–17], as well as the climatic conditions influencing plant biomass formation [18,19].

The assessments of climate impacts on plants are important implications for region-specific adaptation strategies to ensure future food supply of an increasing world population. While the patterns of mean annual precipitation and aboveground net primary productivity relations are highly variable, the underlying processes of these relations are not yet fully understood, and in this way, are still controversial [6]. The impact of changing climate on plant productivity varies and depends on the geographical area [20,21], resilience of plants to adverse conditions [22,23], soil properties, and other factors [24,25]. It is predicted that climate change may lead not only to a reduction in the productivity of grassland land use but also to changes in feed quality, which may have a negative impact on animal productivity and health [26]. Therefore, a more accurate assessment of the impact of grasslands on environmental sustainability can only be made based on data from long-term experiments performed in different climatic and soil zones.

The aims of this study were to determine the change in biomass productivity of natural and managed herbaceous vegetation due to the variation of rainfall amount, and to determine the impact of different land use on soil properties and on the rate of C_{org} sequestration in ex-arable *Arenosol* of the temperate climate zone using the data of a long-term experiment (1995–2019).

2. Materials and Methods

2.1. Experimental Site Description

Experimental sites were arranged in the Lithuanian Centre for Agriculture and Forestry Voke branch (Vilnius, Lithuania, 54°33′49.8″ N 25°05′12.9″ E) on Endocalcaric Cambic *Arenosol* [27] in 1995. The soil was formed on fluvio-glacial deposits and has the following profile: Ap-AB-Bw-Bk-Ck-2Ck. Carbonates are located at a depth of 80–100 cm. The texture of soil A horizon (by Food and Agriculture Organization is: sand (63 μm –2 mm)—81.0–83.7%, silt (2–63 μm)—11.2–13.7%, and clay (<2 μm)—4.5–5.0% [28]. The experiment location is in the temperate climate zone. The mean annual air temperature (the standard climate norm (SCN)) is +6.0 °C, with mean annual precipitation of 664 mm.

2.2. Field Investigation

The experiment investigated changes in arable land use to different herbaceous phytocenoses: (1) abandoned land (AL), (2) managed unfertilized grassland (MG_{unfert}), and (3) managed fertilized grassland (MG_{fert}). The areas of the land uses under investigation were about 400 m² for AL, 200 m² for MG_{unfert} , and 200 m² for MG_{fert} .

During the study period, a natural vegetation phytocenosis typical of sand soils in this region was formed in the site of abandoned arable land. No agro-technical activities were performed in the abandoned site. The botanical composition of the phytocenoses varied depending on hydrothermal conditions of the growing season and on the duration of the experiment. In 1995, 39 plant species were established in the AL site, and in 2017, 29 plant species. The dominant species were mouse-ear hawkweed (*Pilosella ofcinarum* F. W. Schultz et Sch. Bip.), tall fescue (*Festuca arundinaceae* Schreb.), birds-foot trefoil (*Lotus corniculatus* L.), narrowleaf plantain (*Plantago lanceolata* L.), and annual fleabane (*Erigeron annuus* L.).

A grass–legume mixture was grown in the MG site. In 1995–2006, it included hybrid lucerne (*Medicago varia* L.)—40%, and 4 species of grasses—20% red fescue (*Festuca rubra* L.), 20% brome grass (*Bromus inermis* Leyss.), 10% cock’s-foot grass (*Dactylis glomerata* L.), and

10% meadow-grass (*Poa pratensis* L.). In 2007 and in 2015, the grasses were reseeded. The same grass mixture was grown in 2007–2018, only since 2007, cock's-foot was replaced by timothy (*Phleum pratense* L.). The grasses were fertilized with $N_{60} + {}_{30}P_{90}K_{120}$ in the MG_{fert} site. Nitrogen fertilizers (N_{60}) and phosphorus (P_{90}) and potassium fertilizers (K_{120}) were applied at the beginning of grass vegetation (in the third ten-days of March to the first ten-days of April). The grass was fertilized for the second time with nitrogen fertilizer (N_{30}) after the first grass cutting (during the first ten days of July). During the vegetation period, these grasses were cut twice. The first grass cutting was performed during the flowering phase of alfalfa (in the first ten-days of July). The second cutting was performed in the first ten-days of September. The biomass of the MG site was removed from the experiment area.

2.3. Calculation of Biomass Yield

Grass biomass was calculated in the land use sites each year. The dry matter content in plants was determined after the samples had been dried to constant moisture at 105 °C. Biomass of natural humidity and dry biomass of the plant production were assessed, excluding root biomass. Biomass calculation in the AL site was performed at 5 spots of 0.25 m², and in the MG_{fert} and MG_{unfert} plot, the yield calculation was performed for 48 m² of recorded subplots with 3 replications. Dry matter yield (DM Mg ha⁻¹) was determined. To assess the change in productivity of different land uses, the whole study period (1995–2019) was divided into four subperiods (1996–2000, 2001–2005, 2008–2012, and 2013–2019) and the average biomass DM yield for these periods was calculated. The first (1995) year of grassland formation and the year of reseeded of old managed grassland (2006–2007) are not included in the calculation.

2.4. Meteorological Conditions

Rainfall in May and June is of great importance for the formation of grass biomass, as it grows most intensively during this period [29]. Meteorological conditions according to the amount of precipitation in May and June were assessed according to the deviation from SCN ($SCN \sum_{05-06}$ 122 mm). Normal humidity conditions during the growing season in \sum_{05-06} were considered when the amount of precipitation varied from 100 to 150 mm (deviation \pm 20% SCN). With less than 20% SCN precipitation falling during these months (less than 100 mm), the growing season was described as droughty, and with more than 20% SCN precipitation, it was considered as wet (more than 150 mm). To assess trends in precipitation variations, the entire study period (1996–2019) was grouped into four subperiods (1996–2000, 2001–2005, 2008–2012, 2013–2019), as well as for the purpose of assessing changes in grass biomass yield.

2.5. Soil Sampling

The topsoil (0–25 cm) of the experiment area in 1995 had very similar chemical properties (soil acidity(pH_{KCl}), plant available phosphorus (P_2O_5) and potassium (K_2O), C_{org}) (Table 1), and according this, soil samples (3 joint samples) were taken from each land use plot (AL , MG_{fert} , MG_{unfert}) using a stainless-steel cylindrical soil corer. In 2018, at each site, soils were sampled from A horizon in 3 replicates. The soil samples were air-dried, gently crushed, and passed through a 2 mm mesh sieve.

Table 1. Soil pH_{KCl} and plant available P_2O_5 and K_2O content (mg kg⁻¹) in the soil at the beginning of the experiment (1995) and in 2018.

Measured Parameters	Abandoned Land		Managed Grassland Unfertilized		Managed Grassland Fertilized	
	1995	2018	1995	2018	1995	2018
pH_{KCl}	6.0A	5.8Aa	6.8B	6.0Aa	6.8A	5.6Aa
Available P_2O_5 mg kg ⁻¹	157B	150Ab	177B	77A	177A	264Ac
Available K_2O mg kg ⁻¹	170B	144Aa	174B	70Ab	174A	166Aa

Note. Capital letters in rows indicate a significant difference between soil indices in 1995 and in 2018 ($p < 0.05$) in separate treatments, and lowercase letter in rows indicate a significant difference between treatments in 2018 ($p < 0.05$).

Soil bulk density was determined in the beginning of the experiment (1995) and in 2018 by the Core method using a metal ring pressed into the soil (intact core), and the weight after drying was determined [30].

2.6. Laboratory Analysis

Soil chemical properties were determined as follows:

- pH_{KCl} —by ISO 10390:2005 potentiometric method (1 mol l⁻¹ KCl using a soil/solution ratio of 1:2.5).
- C_{org} —by Duma method (after dry combustion), ISO 10694:1999.
- Plant available P₂O₅ and K₂O were extracted using 0.03 M ammonium lactate (Egner-Riehm-Domingo (A–L) method).

Soil organic carbon stocks in the A horizon were calculated as follows [31]:

$$\text{SOC}_{\text{stock}} (\text{Mg ha}^{-1}) = \text{SOC}_{\text{con}} \times \text{BD}_{\text{sample}} \times \text{depth} \div 10,$$

where SOC_{con} is soil organic carbon concentration (g kg⁻¹), BD is bulk density of the total sample (Mg m⁻³), depth is the thickness of the humic A horizon layer (cm), and 10 is coefficient to calculate SOC stocks in Mg ha⁻¹.

2.7. Statistical Analysis

The statistical analysis was done with SAS software (Version 9.4, Cary, NC, USA, 2012). The DM trait showed significant deviation from the normal distribution. Logarithmic transformation was applied to get appropriate normality. Levene's test for homoscedasticity to test equal variances across sites was applied with the GLM procedure and absolute residuals option. Suitability of parametric methods was approved. Tukey's studentized range (honestly significant difference (HSD)) test was used to carry out multiple comparisons between soil chemical parameters, soil organic carbon (C_{org}) concentrations, and C_{org} stocks influenced by different land use (abandoned, unfertilized managed grassland, fertilized managed grassland) measured in 2018. The probability level was set at 0.05 (*). Standard error (SE) values were used to estimate the deviations of DM from the mean values [32]. A linear and polynomial regression analysis was used to reveal the relationship between biomass DM yield and duration of the experiment, as well as to determine trends in precipitation in 1995–2019.

One-factor analysis of variance (ANOVA) was used to test the effect of time for precipitation using the GLM procedure. Two-factor mixed ANOVA with repeated measures (year) was performed to test the effect of site for DM (GLM procedure) in two ways. In one case, repeated measures were taken as a year effect on DM, and in the other case, as a period (dry, normal, and wet) effect on DM. Also, two-factor ANOVA was used to test the effects of site and growing season conditions (dry, normal, and wet, as described above) for DM, including the interaction. The significance of the replicate effect on DM was tested separately, and it was not significant, so it was not included in the ANOVA models. Two-factor ANOVA was performed to test the effect of time and management for soil properties (GLM procedure). The regression analysis was performed using the QUANTSELECT procedure that models the effects of a response variable. The quantile level was set to 0.5 in the model and the effect selection method as 'forward'. The analysis was used to determine the dependence of DM on precipitation time and amount in separate sites, and also the dependence of DM on soil properties. Second- or third-degree polynomials were used just to illustrate trends in biomass DM yield, and coefficient of determination was simply used as an indicator that the equation fits for the data. The SAS CORR procedure was used for the Pearson correlation estimates.

3. Results

3.1. Precipitation in 1995–2019

A comparison of the actual precipitation in all study periods with the SCN shows that in 1996–2019, the average annual precipitation tended to slightly increase.

In the territory of Lithuania, the SCN of May rainfall is 54 mm, and in June it is 68 mm (Σ_{05-06} 122 mm) [33]. During the period 1996–2019, 11 years (1997, 1998, 2000, 2001, 2002, 2003, 2007, 2012, 2013, 2014, and 2017) were normally humid, and rainfall amount in May–June ranged from 100 to 150 mm, 6 years (1999, 2006, 2015, 2016, 2018, and 2019) were arid (rainfall lower than 100 mm), and 7 years (1996, 2004, 2005, 2008, 2009, 2010, and 2011) were wet—more than 150 mm of rainfall fell (Figure 1). Rainfall trends over the period 1996–2019 showed an overall decreasing tendency (R^2 0.41) in its amount in May and June, when grass biomass was growing most intensively. More accurately, the variation trend is described by a third-order polynomial function, the curve of which reflects that the decreases and increases in rainfall have a certain periodicity. May and June were rainier in the period 2004–2012, and starting from 2013, these months were repeatedly more droughty. Estimation of precipitation differences by grouping them into subperiods (1996–2000, 2001–2005, 2008–2012, 2013–2019) confirmed the same regularities. The rainiest May and June were in 2008–2012 (average subperiod precipitation was 185.8 mm), and in 2013–2019, precipitation fell twice as much (average 92.9 mm) (Figure 2). ANOVA revealed that periods did not significantly differ in precipitation in May or June, but they did in the sum of two months. The two-factor ANOVA test of site and growing season conditions' (dry, normal, and wet) effects for DM resulted in both being significant ($p < 0.0001$), as well as their interaction, $p = 0.0005$. The two-factor mixed ANOVA test of site with repeated measures of year for DM showed the significance of $p < 0.0001$ for the effects, including the interaction. The same model, however using the growing seasons instead of years with the precipitation amount revealed lower significance levels: for site it was $p < 0.0001$, for period, $p = 0.0014$, and for the interaction, $p = 0.0107$.

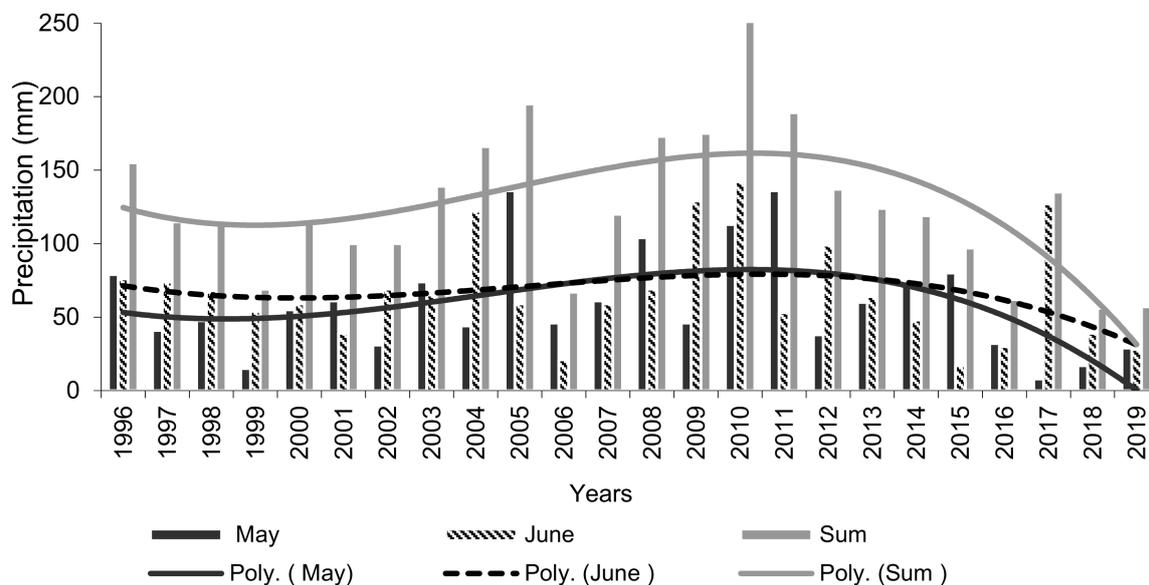


Figure 1. Monthly rainfall in May and June and sum in May and June between 1996 and 2019 in Voke and the regression line between 1996 and 2019.

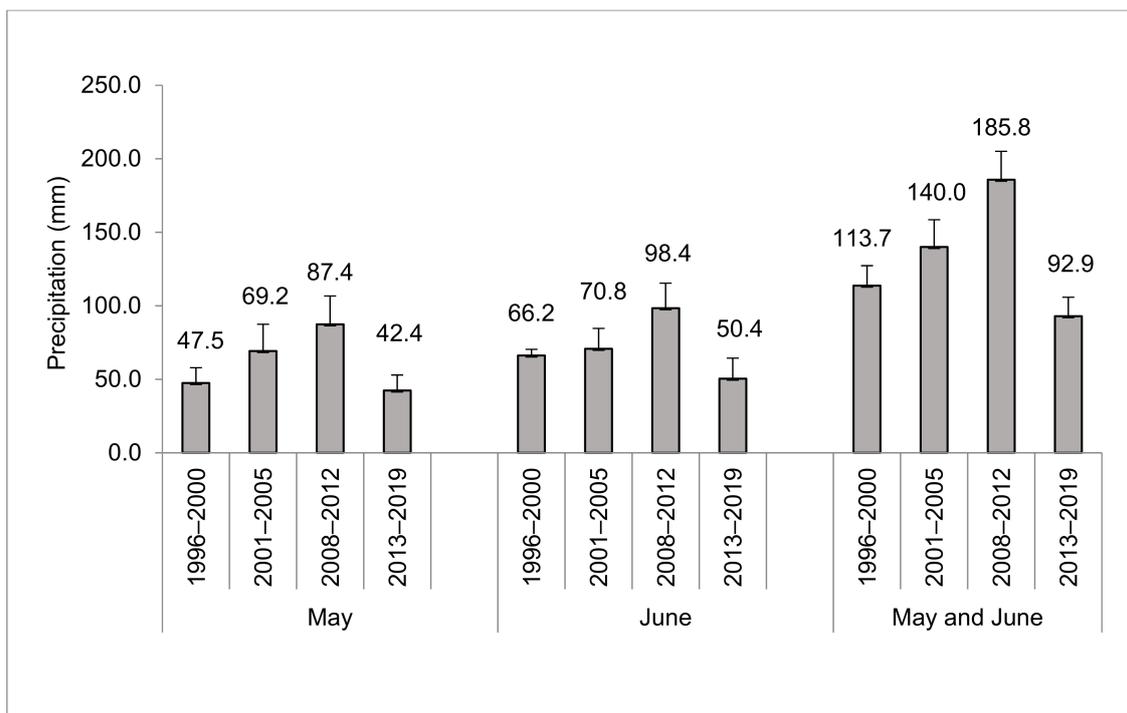


Figure 2. Estimation of precipitation differences by grouping them into subperiods (1996–2000, 2001–2005, 2008–2012, 2013–2019).

3.2. Grassland Biomass Productivity

According to 1996–2019 data, the annual DM productivity of abandoned land vegetation reached an average of 1.76 Mg ha^{-1} DM (Table 2, Figure 3). Rainfall amounts in May–June did not have any significant effect on the natural grassland productivity—the average biomass yield in dry and wet years varied from 1.77 to 1.55 Mg ha^{-1} . However, due to particularly unfavorable conditions (lower air temperatures, late frosts, longer dry periods, lower amounts of solar radiation, etc.), the biomass of abandoned land decreased almost 2.0 times compared to the average plant productivity for the whole study period (1996–2019), and due to favorable hydrothermal conditions, it increased by 56%. Precipitation amount in May had more than twice as large effect on DM compared to June and the relationship with DM was negative (-0.19).

Unfertilized managed grasses were more productive compared to natural vegetation, with an average yield of 2.91 Mg ha^{-1} DM for 1996–2019. Fertilization with NPK fertilizers increased the productivity of managed grasses by 83%. Under unfavorable growth conditions, the productivity of $\text{MG}_{\text{unfert}}$ grasses decreased 2.6 times, and that of grasses fertilized with NPK decreased 2.4 times. The higher productivity of managed grasses on *Arenosol* was determined in those years when the rainfall amount in May and June was close to the SCN (115.6 mm): in the MG_{fert} subplot, DM yield reached 9.46 t ha^{-1} , and it reached 7.03 t ha^{-1} in the $\text{MG}_{\text{unfert}}$ subplot. Precipitation amount in the $\text{MG}_{\text{unfert}}$ site influenced DM much more than in the AL site, and the amount in June had a larger effect on DM (-0.29^*) compared to May.

Managed grasses fertilized with mineral fertilizers and unfertilized ones increased biomass yield at optimal rainfall (100 – 150 mm in May–June). Under dry conditions, the productivity of $\text{MG}_{\text{unfert}}$ grasses decreased by 44.4%, that of NPK-fertilized grasses decreased less, by 16.9%, and under excess rainfall (more than 150 mm), it decreased by 110.8% and 50.4%, respectively. Precipitation amount in May had more than twice as large effect on DM compared to June, with the same tendency, just stronger, in the AL site (-0.35^*). Effect selection among precipitation time on DM using the QUANTSELECT procedure included intercept and sum of precipitation in May and June to the predicted

model. In case of the MG_{unfert} site, it was intercept and May, and in case of the AL site, it was intercept and June.

Table 2. Biomass mean values, standard error (SE), and amplitude of different grass phytocenoses (DM Mg ha⁻¹) in *Arenosol* (1996–2019).

Land Use	Average ± SE 1996–2019	Min	Max	Median	Variation (%)	Rainfall Amount in May–June (mm)		
						<100	100–150	>150
AL	1.76 ± 0.105	0.90	2.78	1.75	33.9	1.77 ± 0.284	1.90 ± 0.170	1.55 ± 0.098
MG_{unfert}	2.91 ± 0.327	1.10	7.03	2.54	42.6	2.57 ± 0.411	3.71 ± 0.576	1.76 ± 0.182
MG_{fert}	5.33 ± 0.469	2.25	9.46	5.65	27.8	5.21 ± 0.817	6.09 ± 0.785	4.05 ± 0.511

Note. Abbreviations: AL, abandoned land; MG_{unfert} , managed unfertilized grassland; MG_{fert} , managed fertilized grassland; SE, standard error. AL and MG_{unfert} subplots were unfertilized, MG_{fert} subplot was fertilized.

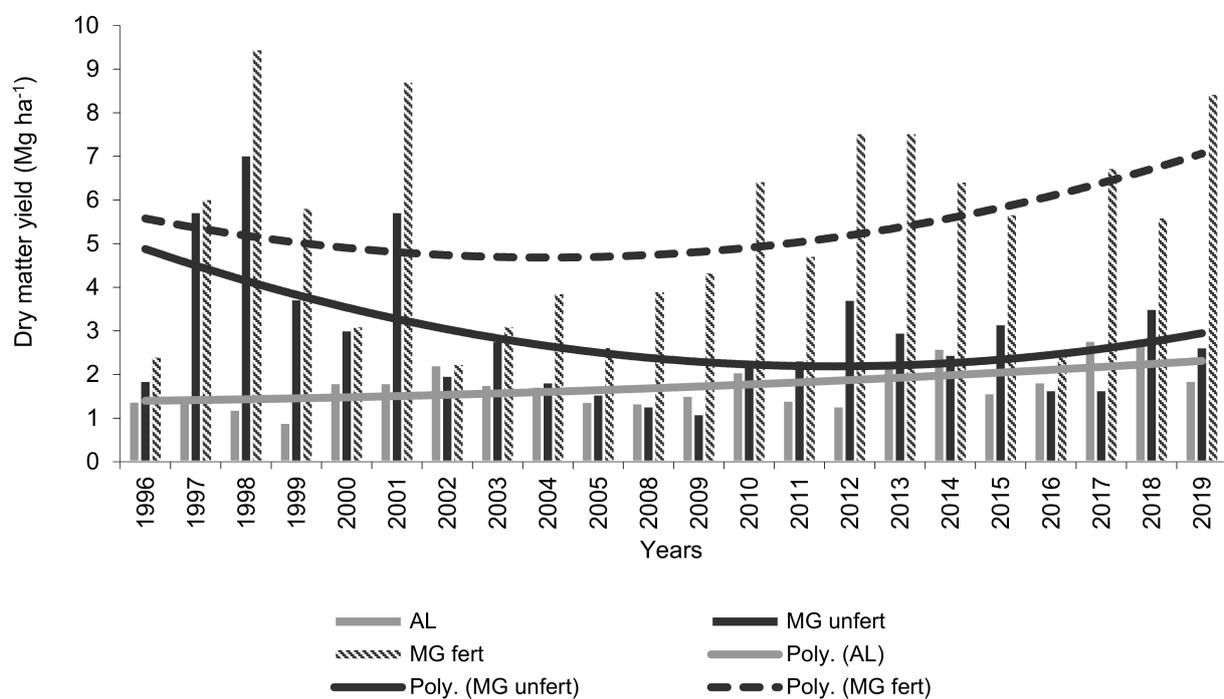


Figure 3. Long-term data detailing the biomass DM yield (Mg ha⁻¹) of grassland land uses in 1996–2019 and the regression line between 1996 and 2019. Note. Abbreviations: AL, abandoned land; MG_{unfert} , managed unfertilized grassland; MG_{fert} , managed fertilized grassland. AL and MG_{unfert} subplots were unfertilized, MG_{fert} subplot was fertilized.

The variability in DM yield of AL grass biomass was lower compared to that of MG_{unfert} grasses and accounted for 33.9%. Regression analysis showed a positive increasing trend in AL DM yield over the study period (R^2 0.68) (Figure 4). Variations in available phosphorus concentration in AL soil were insignificant, and available potassium decreased by 26 mg K₂O kg⁻¹ on average (Table 1). However, the decrease was not critical to limit the formation of natural vegetation biomass. The studies carried out in 2018 showed that the soil could be described as potassium-rich based on the concentration of available potassium. The comparison of soil properties between 1995 and 2018 resulted in significant differences in the MG_{unfert} site. Soil pH correlated negatively with DM, and the other properties had positive estimates, with the largest for carbon concentration and P₂O₅ (0.84 * and 0.72).

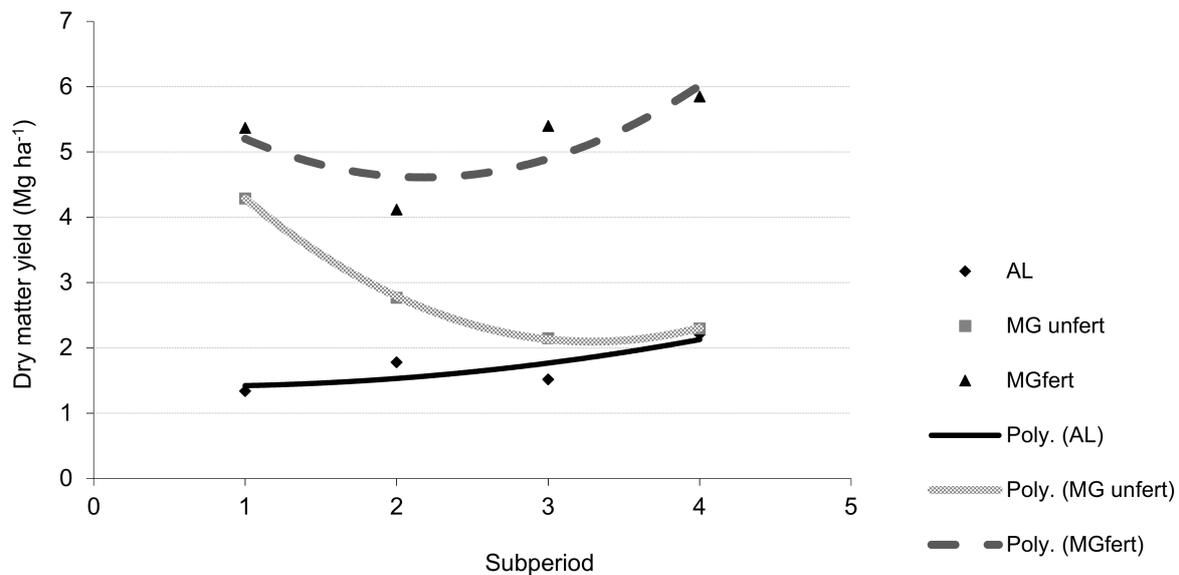


Figure 4. Trends in biomass DM yield (Mg ha^{-1}) of different grassland land uses in 1996–2019 (subperiod: 1—1996–2000; 2—2001–2005; 3—2008–2012; 4—2013–2019). Note. Abbreviations: AL, abandoned land; $\text{MG}_{\text{unfert}}$ —managed unfertilized grassland; MG_{fert} , managed fertilized grassland. AL and $\text{MG}_{\text{unfert}}$ subplots were unfertilized, MG_{fert} subplot was fertilized.

During the first study period (1996–2005), the productivity of $\text{MG}_{\text{unfert}}$ ($4.29\text{--}4.12 \text{ Mg ha}^{-1}$ DM) was 3.2–1.6 times higher compared to the productivity of AL vegetation ($1.34\text{--}1.78 \text{ Mg ha}^{-1}$ DM). However, as the study period lengthened, the amounts of plant nutrients (phosphorus, potassium) in soil decreased in the $\text{MG}_{\text{unfert}}$ subplot, which resulted in a decrease in the grassland biomass yield (R^2 0.999) (Table 1). Available phosphorus decreased from 177 to 77 $\text{mg P}_2\text{O}_5 \text{ kg}^{-1}$, and available potassium from 174 to 70 $\text{K}_2\text{O kg}^{-1}$ in the A horizon of the unfertilized managed grassland. With nutrient deficiencies, grasses could not produce high amounts of biomass. During the last study period (2013–2019), the average DM yield of this land use was 2.30 t ha^{-1} , and it was not significantly different from the biomass yield in the abandoned site (2.21 Mg ha^{-1} DM). Effect selection among soil properties on DM using the QUANTSELECT procedure included intercept, carbon sequestration, P_2O_5 , and pH in the predicted model.

Two-factor ANOVA in testing the effect of time and management for soil properties revealed that time effect was significant for carbon sequestration, K_2O , and pH, while the site effect was significant for P_2O_5 and K_2O .

3.3. Organic Carbon Sequestration in Different Grassland Soils

By transforming the type of land use in *Arenosol* from arable land to grassland, the aim was to increase the accumulation of carbon in soil, thus improving its physical and chemical properties by stopping degradation processes. Carbon sequestration in the AL and MG sites took place in two directions— C_{org} concentration in the A horizon changed, and the thickness of this horizon increased as well. Compared to the A horizon thickness at the beginning of the experiment, it increased most in the AL site, by 6 cm (Table 3).

The A horizon increased in the MG_{fert} by 4 cm, and in the $\text{MG}_{\text{unfert}}$ by only 2 cm. Perennial grass roots and fallen material of the aboveground biomass also affected C_{org} concentrations. After 23 years of cultivation, higher C_{org} concentration (11.3 mg kg^{-1}) was found in the A horizon of the MG_{fert} subplot soil. In the soil of $\text{MG}_{\text{unfert}}$ and AL, its concentration in the A horizon increased by 0.8 and 0.2 $\text{mg kg}^{-1} \text{ C}_{\text{org}}$ accordingly. C_{org} stocks increased most (+27.5%) in the AL soil, in the MG_{fert} they increased by 18.4%, and in the $\text{MG}_{\text{unfert}}$ by 12.5%.

Table 3. Organic carbon accumulation in the A horizon of soils under different land uses.

Land Use	Thickness of A Horizon (m)		C _{org} (mg kg ⁻¹)		C _{org} (Mg ha ⁻¹)		C _{org} (Mg ha ⁻¹ year ⁻¹)
	1995	2018	1995	2018	1995	2018	
AL	0.28	0.34	10.2A	10.4Ba	38.0A	48.5Ba	0.455
MG _{unfert}	0.28	0.30	9.9A	10.7Ba	39.1A	44.0Ba	0.212
MG _{fert}	0.28	0.32	9.9A	11.3Ba	40.2A	47.6Ba	0.321

Note. Abbreviations: AL, abandoned land; MG_{unfert}—managed unfertilized grassland; MG_{fert}, managed fertilized grassland. Capital letters in rows indicate a significant difference between soil indices in 1995 and in 2018 ($p < 0.05$) in separate treatments, and lowercase letter in columns indicate a significant difference between treatment in 2018 ($p < 0.05$).

4. Discussion

The cenoses of natural grasses formed in infertile soils from the existing plant seed bank are adapted to nutrient deficiencies and variable moisture regimes, therefore the variation of grass DM yield during dry or wet vegetation periods was not large. Having assessed different vegetation periods of May and June in terms of the amounts of rainfall (Table 2), it was found that the DM yield varied from 1.77 Mg ha⁻¹ in arid years (rainfall amount $\Sigma_{05-06} < 100$ mm) to 1.55 Mg ha⁻¹ in wet years (rainfall amount $\Sigma_{05-06} > 150$ mm). Researchers have very different opinions regarding the influence of climatic changes on the yield of grasslands. The authors of Reference [34] suggest that this may depend on research methodology, conditions, and time periods. The authors of Reference [35] examined the seasonal impacts of climate variability on 27 years of grass productivity in a temperate, humid grassland, and found that drought and high-intensity precipitation reduced grass productivity only during a 110-days period, whereas high temperatures reduced productivity only during 25 days in July. Other researchers [36], having studied the correlations between grass productivity and air temperature and precipitation, argue that productivity is affected both by meteorological conditions of a current year and those of previous years.

In this experiment, the change in productivity of natural grasses over a 23-year period showed that the DM yield tended to increase with lengthening of the study period. It should be noted that over a five-year period, the average DM yield data showed a stronger correlation ($R^2 = 0.68$) with the duration of sward functioning compared to the change trend determined with the annual DM yield data ($R^2 = 0.34$) (Figures 3 and 4). The trend of a steady increase in DM yield at the AL site could be attributed to C_{org} stocks' accumulation in the A horizon, which accordingly facilitated the formation of grass biomass. The increase in organic matter stocks is closely related to the moisture-holding capacity of soil, activating the circulation of nutrients in soil [37,38]. Water movement in soil is closely linked with storage because water potential is a function of water content. Water flow is also influenced by texture and structure. Soil structure is highly relevant to water management in soils because it is subject to change either through deterioration by improper management, or to improvement through additions of soil organic matter. Also, water content helps to activate the labile soil nutrients. The rate of C_{org} accumulation was found to change with lengthening a land use period [39,40]. According to the authors of Reference [41], the restoration of soil properties following arable land abandonment is likely to take place during the first 15–20 years. In contrast, according to other researchers [42], the increase of C_{org} stocks in soil is slower during the first ten-days of grass cultivation (1–13 years) compared to the second ten-days (13–22 years). Apparently, the rate of C_{org} sequestration can vary depending on the type of herbaceous plants, soil properties, and hydrothermal conditions. In *Arenosol*, C_{org} concentration in the A horizon of the AL site increased by 2.0% over 23 years, and the horizon thickness by 6 cm. The annual C_{org} accumulation was 0.455 Mg ha⁻¹. The authors of Reference [19] reported that in temperate climate zones, the average C_{org} sequestration rate in abandoned land can reach 0.75 Mg ha⁻¹ C_{org}. Changes in chemical properties of the AL soil over 23 years indicate that available phosphorus concentrations changed least in the A horizon in comparison with MG_{unfert}, as the phosphorus accumulated in plant biomass remained on the soil surface after mineralization. This data confirms the statement by the

authors of Reference [43], claiming that leaving grass biomass on the soil surface promotes the formation of phosphorus compounds that are bioavailable to plants. Available potassium concentration in the AL decreased by $26 \text{ mg K}_2\text{O kg}^{-1}$ (Table 1), as this element was easily leached in *Arenosol*. It was found that in *Arenosol*, potassium was leached from the A layer with precipitation $14.5\text{--}43.4 \text{ kg K ha}^{-1}$ per year [44]. Nevertheless, in the climatic zone of this experiment, the amount of leaching of the basic elements has been determined: $131.4\text{--}180.1 \text{ kg Ca ha}^{-1}$ per year and $15.8\text{--}29.9 \text{ kg Mg ha}^{-1}$ per year. Even though leaching of basic elements (Ca, Mg) increased soil acidity (-0.2 units of pH_{KCl} over 23 years), it did not cause any significant deterioration of soil properties. In that way, leaving infertile arable land for self-overgrowth can both significantly stabilize degradation processes in *Arenosol* and increase C_{org} sequestration in the soil. Increasing C_{org} concentration in soil creates better conditions for the growth of grass biomass.

In contrast to the abandoned land, DM yield decreased in the unfertilized managed grassland as the research period lengthened. A medium-strength negative correlation (R^2 0.27) was found for the trend of changes according to the annual biomass yield and a very strong (R^2 0.999) correlation was found for yield changes by five-year periods. The assessment differences are due to the fact that a consistent decrease in yield in the $\text{MG}_{\text{unfert}}$ began to become apparent after 12–15 years of grassland use, when the concentration of available nutrients in soil decreased significantly.

Changes of different direction in the biomass yields of the AL and $\text{MG}_{\text{unfert}}$ during the experiment, with the same variation of climatic factors, suggest that changes in *Arenosol* chemical properties (C_{org} sequestration, concentrations of available P and K) affect grassland biomass productivity more than variations in hydrothermal conditions in the course of vegetation during different years.

Fertilization of MG with mineral fertilizers ($\text{N}_{60+30}\text{P}_{90}\text{K}_{120}$) significantly increased biomass productivity. Biomass yield averaged 5.33 Mg ha^{-1} DM, which is 3.03 times higher than the average produced by AL vegetation. A similar efficiency of chemical fertilizers on the productivity of grasses has been established in other countries of Europe [45]. However, they note that fertilizer should be applied according to the requirements based upon soil analysis and the removal of NPK should be replaced to maintain soil levels and the botanical composition of the grassland. A positive increase in DM yield of the MG_{fert} was observed with lengthening of the study period (R^2 0.65). This could be related to C_{org} accumulation in the A horizon, as in the AL use. Mineral fertilizers not only increase biomass productivity but also mitigate the negative impact of meteorological conditions on plant growth and ensure a more stable biomass yield. For example, the weather conditions have a significant impact on the yield and quality of plants. The weather in the vegetation season can affect more than half of the yield fluctuation amplitude, and fluctuations in the chemical composition are also affected by the heat and moisture regimes. Additionally, the yields can be significantly increased by fertilization because the fertilizer affects the yield variation. The variation of DM yield decreased by 14.8% compared to the $\text{MG}_{\text{unfert}}$.

Optimal fertilization with NPK fertilizers caused insignificant changes in available K (-8 mg kg^{-1}) in soil, as well as available P (87 mg kg^{-1}). K decreased because the rate of fertilizers was insufficient to cover the accumulation of K in plant biomass yield. P increased as a certain proportion of phosphorus from the fertilizer was not used by plants and accumulated in the topsoil. However, it should be noted that according to our data, mixtures of alfalfa and grasses used a lot of calcium (average $78 \text{ kg Ca ha}^{-1} \text{ year}^{-1}$) and magnesium (average $46 \text{ kg Mg ha}^{-1} \text{ year}^{-1}$) to produce yield. The decrease in basic element concentrations in a 23-year period caused the A horizon acidification (-0.8 pH units). In grassland, soil acidification is an ongoing process under humid climate conditions [46], and therefore monitoring of soil acidity variation is necessary to avoid adverse effects.

C_{org} sequestration in the $\text{MG}_{\text{unfert}}$ soil was slower compared to the AL. Over the years, its reserves in such land use increased by only $0.212 \text{ Mg ha}^{-1} \text{ year}^{-1}$ C_{org} because, contrary to the abandoned land, organic matter accumulation in soil occurred only due to fallen grass material and root system biomass. Without the use of mineral fertilizers in the managed

grassland, further degradation of sandy soil properties takes place—concentrations of available nutrients decrease, and soil becomes acidic. These changes confirm that the use of grassland for agricultural production requires the maintenance of a nutrient balance with fertilizers and the use of lime fertilizers in acid soils to reduce soil acidity.

The results of long-term studies of AL and MG productivity have shown that biomass yield in different land uses depends not only on precipitation amount but also on variable soil fertility; therefore, the long-term dynamics of yield and soil fertility variations need to be taken into account when assessing the advantage of different grassland land uses in ex-arable soil.

5. Conclusions

The type of low-productivity arable land use conversion to grassland in *Arenosol* should be chosen according to the priorities of objectives such as increasing C_{org} sequestration or reducing socially sensitive consequences of agricultural abandonment.

In the temperate climate zone, it is economically beneficial to introduce natural grasslands to reduce the degradation of soils. In AL, C_{org} sequestration is faster, and it improves other soil properties, especially hydrophysical ones and sorption capacity, as well as reduces CO_2 emissions. In order to reduce the negative social impact due to the conversion of low-productivity arable lands to AL, the introduction of managed grasslands is also possible in *Arenosol*. The productivity of MG_{fert} was 3.03 times higher than that of the AL. However, in order to achieve sustainable soil use in such a land, balanced fertilization with mineral fertilizers must be applied, and variation of pH must be monitored in acidic soils. Fertilizers significantly increase the biomass productivity of MG, reduce the variability of biomass yield due to changes in climatic conditions, improve soil fertility parameters, and increase C_{org} sequestration, and this ensures a long-term increasing trend of grassland biomass productivity.

The study results revealed that climate change in the temperate climate zone had a smaller impact on grass biomass yield compared to changes in soil properties due to long-term land use. In the temperate climate zone, spring moisture reserves in soil can mitigate the effects of rainfall deficiency on grass biomass formation during the intensive growth stage (May–June). In long-term natural and fertilized managed grasslands, the A horizon thickness and C_{org} concentration increase, leading to better conditions for grass development and a consistent increase in grass biomass productivity.

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