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ORIGINAL PAPER

THE USE OF AGRI-FOOD INDUSTRIAL WASTEWATER FOR GRASSLAND IRRIGATION*

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Abstract

The objective of this study was to determine the influence of 20-year sprinkler irrigation of permanent grassland with potato starch and brewery wastewater on the botanical composition of sward, and the yield and nutritional value of hay. The experiment was carried out in Kupiski-Jednaczewo, near Łomża, NE Poland (approximately 600 ha). Potato starch and brewery effluents were mixed at a ratio of 1:0.4. Wastewater was applied in autumn and after the first harvest, at an annual dose of 200-300 mm. The analyzed wastewater contained on average (mg dm^{-3}): N – 223, P – 48, K – 285, Ca – 80, Mg – 46 and Na – 68. The floristic composition of meadow sward was determined before the first harvest in 1998, 2003, 2008, 2013 and 2018, while the yield was determined on trial plots. Five major floristic types of grassland communities were identified based on the percentage of dominant species (above 20% share of the sward). Herbage samples were collected for botanical-gravimetric and chemical analyses. Soil samples were collected in 1991 and 2018. Chemical analyses of soil and plant material were performed by standard methods. The following floristic types of grassland communities developed: *Alopecurus pratensis* (Ap), *Arrhenatherum elatius* (Ae), *Dactylis glomerata* + *Festuca rubra* (Dg+Fr), and *Poa pratensis* + *Dactylis glomerata* (Pp+Dg), *Phalaris arundinacea* + *Glyceria maxima* (Pha+Gm), and the *Festuca rubra* + *Anthoxanthum odoratum* (Fr+Ao) community in the control treatment (non-irrigated grassland). The content of P, K, Fe, Cu, Mn and Zn increased, whereas the content of Ca, Mg and Na, and pH levels decreased in the analyzed soils. Regardless of the floristic type of sward, the yield of grassland irrigated with wastewater was significantly (1.6 to 2.8-fold) higher than the yield of non-irrigated grassland. Hay harvested from wastewater-irrigated meadows met the nutrient requirements of animals in terms of crude fiber, ash and fat, excluding total protein.

Keywords: sprinkler irrigation of grassland with wastewater, plant communities, nutritional value of hay.

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INTRODUCTION

Sprinkler irrigation of permanent grasslands with industrial effluents from agri-food processing is one of the cheapest and most effective methods of wastewater treatment in the soil and plant environment (Kutera, Czyżyk 1992, Talik, Pławiński 1995, Wu et al. 1996, Grabowski, Bieniek 2004, Baryła 2005, Charmley et al. 2006, Acar et al. 2009, Li et al. 2010, Hamilton et al. 2011, Bosak et al. 2016, Yong 2017). Wastewater generated in the agri-food industry can be used in agriculture because it contains nutrients of natural origin and is characterized by satisfactory sanitary quality (Smith 1976, Uhlman, Burgard 2001, Arienzo et al. 2009, Aryal, Reinhold 2015). Food and agricultural waste includes potato-processing wastewater (Wang et al. 2007, Singh, Swami 2014) and brewery effluents (Nyilimbabazi et al. 2011, Senthilraja et al. 2013). The mineralization of organic substances supplied through wastewater irrigation increases the amount of nutrients available to plants in the turf layer (Baryła 2005, Charmley et al. 2006, Arienzo et al. 2009, Römheld, Kirkby 2010, Hamilton et al. 2011, Buelow et al. 2015). Plant communities in grasslands irrigated with wastewater often undergo dynamic changes. The viability of species in the sward increases or decreases, turf loosening is observed, weed infestation increases, and the quantity and quality of green fodder decrease (Mikhailova et al. 2000, Baryła 2005, Grabowski et al. 2008, Čop et al. 2009, Kotlarz et al. 2010, Michaud et al. 2015, Andueza et al. 2016, Hejcman et al. 2016). Therefore, the succession of plant communities in grasslands that are sprinkler irrigated with wastewater should be investigated in order to maintain the desired floristic composition of sward and its high productivity as well as proper content of nutrients in feed.

In view of the above, the aim of this study was to determine the effect of 20-year sprinkler irrigation of Kupiski-Jednaczewo permanent grasslands with potato starch and brewery wastewater on the botanical composition of sward, and the yield and nutritional value of hay.

MATERIALS AND METHODS

The study was conducted in the wastewater treatment and use center in Kupiski-Jednaczewo, near Łomża, NE Poland (approximately 600 ha), which has used facilities for sprinkler irrigation with wastewater since 1992. Potato starch and brewery effluents were mixed at a ratio of 1:0.4 in a storage reservoir. Wastewater was applied every year in autumn (October--November) and after the first harvest (May-June), at an annual dose of 200-300 mm (split in half-doses). The analyzed wastewater contained on average (mg dm^{-3}): N – 223, P –48, K – 285, Ca – 80, Mg – 46 and Na – 68.

Supplementary mineral fertilization was not applied during sprinkler irrigation.

The analyzed grasslands developed on arenosol subtypes, classified according to the Polish Soil Classification System (Kabała et al. 2019): gleyic arenosol (soil organic matter content in the top humus layer at the beginning of the experiment was 25.94%), semimurshic arenosol (soil organic matter content at the beginning of the experiment was 12.77%), and semimurshic arenosol (soil organic matter content at the beginning of the experiment was 5.40%) – Table 1 (Grabowski, Bieniek 2004). All analyzed soils share the arenimurshic surface diagnostic horizon, with a thickness of 20 to 27 cm, developed on loose sand (Particle size distribution … 2009). Before sprinkler irrigation (1991), the analyzed soils were characterized by slightly acidic pH, very low content of phosphorus and potassium, low to moderate content of magnesium and calcium, low content of copper and zinc, moderate to high content of manganese, and high iron content (*Fertilizing* … 1990). Gleyic arenosols were richer in nutrients than semimurshic arenosols (Table 1).

The experiment began in 1991 (before wastewater irrigation was started in the Kupiski-Jednaczewo centre). In 1992, the site was reclaimed and grassland was established by full cultivation (ploughing and sowing). In the early spring of1991 and 2018, soil samples were collected in habitats typical of the research site to determine the basic chemical properties of soil with standard methods, which was accomplished in the Chemical and Agricultural Research Laboratory in Olsztyn, Poland. The following determinations were made: P, K, Mg and Fe in 1 mol HCl dm^{-3} (Ostrowska et al. 1991), Mn, Cu and Zn in 0.5 mol HCl dm^{-3} (Sapek, Sapek 1997), Ca and Na by extraction with 0.03% acetic acid, and soil organic matter by the Turin's method.

The floristic composition of meadow sward was evaluated before the first harvest in 1998, 2003, 2008, 2013 and 2018, by the Klapp method on an 11-degree scale (Klapp 1963); yield was determined on trial plots (area 1 m^2). The first harvest was collected at the early phase of earing of dominant grass species in the sward. Names of vascular plant species follow Mirek et al. (2002). The following floristic types of grassland were identified according to the Prończuk method (Prończuk 1962), as they developed in response to sprinkler irrigation with wastewater. The following were distinguished based on the percentage of dominant species (above 20% share of the sward):

– Ap – *Alopecurus pratensis*,
– Ar – *Arrhenatherum elatius*,
– Dg + Fr – *Dactylis glomerata* + *Festuca rubra*,
– Pha + Gm – *Phalaris arundinacea* + *Glyceria maxima*,
– Pp + Dg – *Poa pratensis* + *Dactylis glomerata.*
– The Fr + Ao – *Festuca rubra* + *Anthoxanthum odoratum* community developed in the control treatment without irrigation.

Table 1

Chemical composition of humus layer of the wastewater irrigated soils

Soil classification	Years	SOM	pH_{KCl}	P	K	Mg	Ca	Na	Cu	Mn	Fe	Zn	Salinity
		(%)		(g kg^{-1} DM of soil)					(mg kg^{-1} DM of soil)				(g NaCl dm^{-3}
Gleyic arenosol* Eutric Gleyic Arenosol (Humic)**	1991***	25.94	5.8	11.7	16.4	61.5	133.0	5.3	2	98	2884	2	0.5
	2018	23.00	5.3	38.0	98.6	55.2	70.8	2.9	5	147	7250	8	0.2
Semimurshic arenosol* Eutric Arenosol (Humic, Nechic)**	1991***	12.77	5.7	9.2	12.9	43.4	71.2	8.2	1	203	3640	2	0.3
	2018	11.84	5.3	26.9	49.9	29.1	57.4	2.6	5	94	5862	7	0.2
Semimurshic arenosol* Eutric Arenosol (Nechic)**	1991***	5.40	6.3	5.2	8.3	27.0	49.4	5.0	1	118	1610	2	0.3
	2018	5.15	5.2	33.2	72.6	21.0	24.1	2.5	5	147	5350	5	0.3

* – according to the Polish Soil Classification 2019 (KABAŁA et al. 2019),
** – according to WRB 2015 (IUSS Working Group WRB, 2015),
*** – before irrigation,
SOM – soil organic matter content.

Herbage samples for botanical-gravimetric analyses (1 kg of fresh mass) and chemical analyses (1 kg of fresh mass) were collected from the aforementioned grassland floristic types. A fractional botanical-gravimetric analysis was performed to determine the proportions of economically important and unimportant grass species, legumes, herbs and weeds on a dry matter basis. The chemical analyses of plant material were conducted by standard methods in the Department of Animal Nutrition and Feed Science, Faculty of Animal Bioengineering of University of Warmia and Mazury in Olsztyn: nitrogen – by the Kjeldahl method, crude fiber – by the method proposed by Henneberg and Stohmann, crude fat – by Soxhlet extraction, and crude ash – by incineration in a muffle furnace at a temp. of 550°C (Nazaruk et al. 2009). The nutrient content of meadow sward was expressed on a dry matter basis. Only mean values referring to determined floristic types and the whole studied period are presented in figures. It should be noted that data labeled as Fr + Ao in all figures refer to the control treatment (without irrigation). Statistical analyses were performed using Statistica 13 software; arithmetic means and 95% confidence intervals were calculated.

RESULTS AND DISCUSSION

After 20 years of sprinkler irrigation with wastewater, the nutrient content of soil increased as follows: phosphorus higher by 3-6 fold, potassium – 4-9-fold, iron – 1.6-3-fold, copper – 2.5-5-fold, manganese – 1.2-1.5-fold (excluding semimurshic arenosol with the higher content of soil organic matter 12.77%), and zinc – 2.5-4-fold (Table 1). The content of magnesium, calcium and sodium (particularly in semimurshic arenosol with the lower content of soil organic matter 5.40%) decreased by 1-1.5 fold, 1.2-2-fold and 2-3-fold, respectively. The reaction of the analyzed soils also changed, from slightly acidic (pH KCl 5.7-6.3) to acidic (pH KCl 5.2-5.3). The salt content of soil (0.2-0.3 g NaCl dm^{-3}) remained within the normal range, safe for fodder crops (Grabowski, Bieniek 2004, Arienzo et al. 2009, Römheld, Kirby 2010, Singh, Swami 2014, Buelow et al. 2015, Bosak et al. 2016).

Before 1991, grasses of little economic importance predominated in meadow sward: *Anthoxanthum odoratum*, *Agropyron repens*, *Bromus hordeaceus*, *Deschampsia caespitosa* and *Holcus lanatus*. Agronomically important grass species were represented by *Festuca rubra*, found in low quantities. Dicotyledonous plants were represented by the following species: *Cerastium vulgatum*, *Hieracium pilosella*, *Potentilla anserina*, *Stellaria media*, *Taraxacum officinale*, *Rumex acetosa*, *Ranunculus repens* and others.

During the study, considerable changes were observed in the species composition of sprinkler-irrigated grassland (Figures 1-4). As a result of reclamation and establishment of grassland by the method of full cultivation, 5 valuable floristic types of sward were distinguished. After 20 years

of sprinkler irrigation with wastewater, grasses of high economic importance predominated in meadow sward, regardless of soil type (383.4-626.9 g kg^{-1} DM) – Figure 1, whereas low-quality grasses were present in smaller quantities (140.3-351.0 g kg^{-1} DM) – Figure 2, accompanied by herbs and weeds (194.0-262.6 g kg^{-1} DM) – Figure 4. Legumes were encountered sporadically (3.6-68.8 g kg^{-1} DM) – Figure 3. However, only a few valuable grasses, *Alopecurus pratensis*, *Arrhenatherum elatius*, *Dactylis glomerata*, *Phalaris arundinacea*, *Poa pratensis* and *Festuca rubra*, were dominant species in the sward, which indicates that grasslands irrigated with wastewater could be sown with those species, as noted by Kutera, Czyżyk (1992), Talik, Pławiński (1995), Wu et al. (1996), Baryła (2005), Grabowski et al. (2008), Čop et al. (2009), Andueza et al. (2016), and Dindová et al. (2019).

The following grassland floristic types were characterized by the most desirable floristic composition of sward: *Alopecurus pratensis* and *Arrhenatherum elatius*, located on gleyic arenosol (Figures 1-4). The proportion

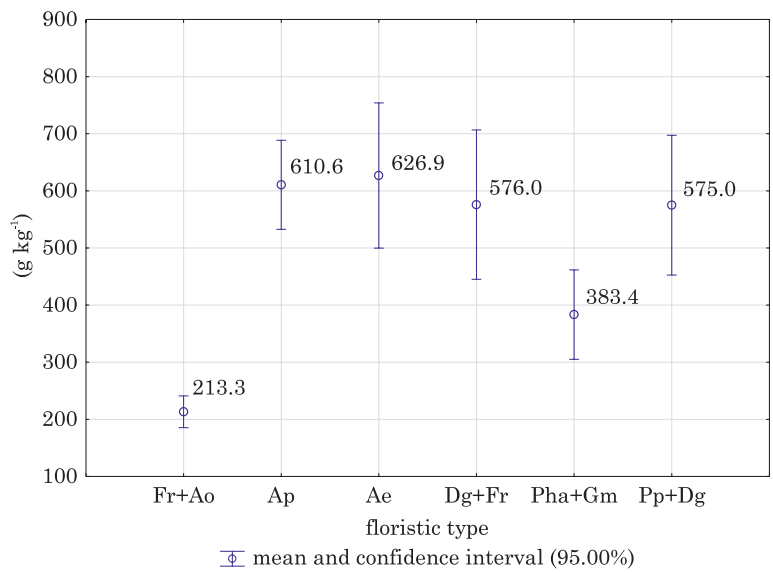

Fig. 1. Participation of valuable grasses in meadow sward after 20 years of irrigation (regardless of soil type)

of valuable grass species ranged from 610.6 to 626.9 g kg^{-1} DM on average, and it was significantly (more than 2.9-fold) higher than in the control treatment. A decrease was noted in the proportions of grasses of low economic importance (140.3-155.4 g kg^{-1} DM), herbs and weeds (194.0-202.0 g kg^{-1} DM) in the sward, whereas legumes were present in low quantities (Figures 1-4).

According to Kryszak et al. (2004), *Alopecurus pratensis* can be found in moist, fertile and periodically flooded habitats, typical of riparian forests. Kitczak and Jankowski (2018) demonstrated that this persistent species can withstand surface flooding. Talik and Pławiński (1995) confirmed that

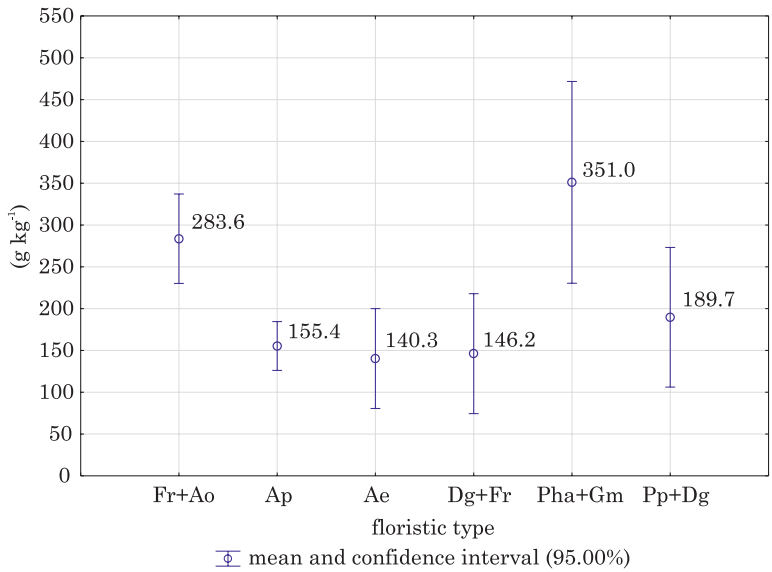

Fig. 2. Participation of low value grasses in meadow sward after 20 years of irrigation (regardless of soil type)

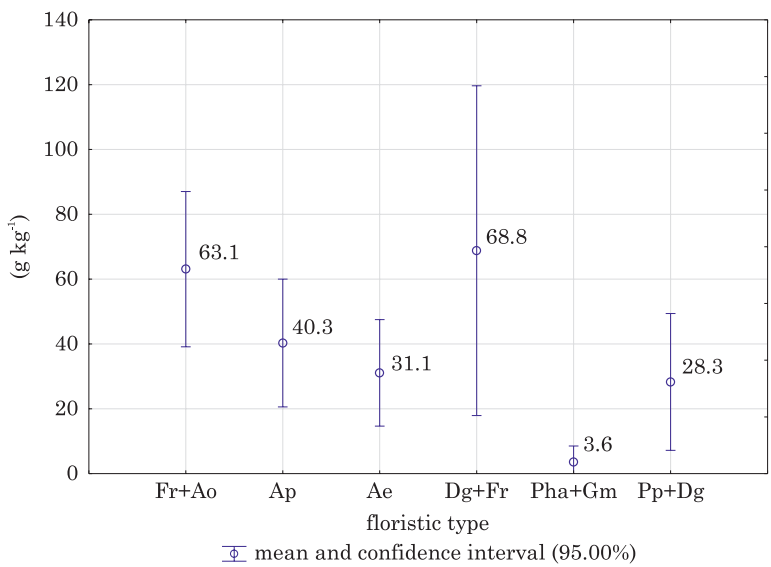

Fig. 3. Participation of legumes in meadow sward after 20 years of irrigation (regardless of soil type)

Alopecurus pratensis is well-adapted to effluent irrigation and can be sown in irrigated grasslands. Czyż et al. (2001) found that *Arrhenatherum elatius* communities often occupy slopes of hills because the species is sensitive to excess soil moisture, which is consistent with the results of this study.

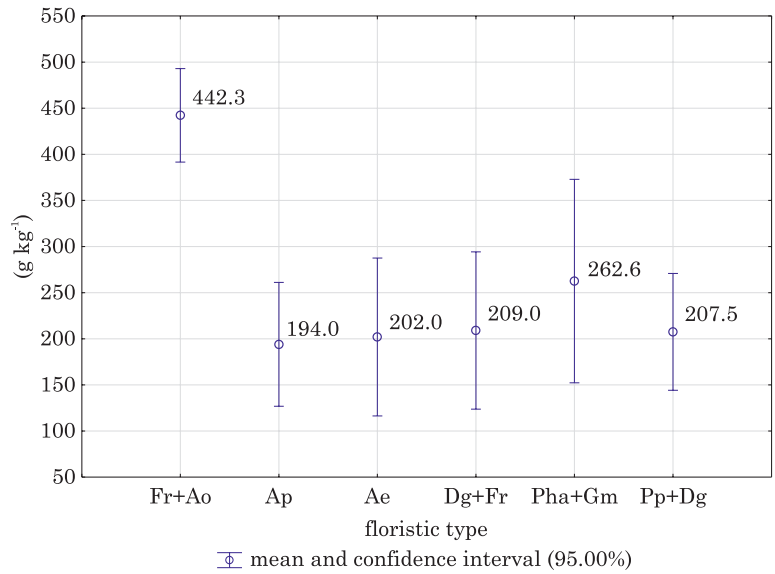

Fig. 4. Participation of herbs and weeds in meadow sward after 20 years of irrigation (regardless of soil type)

In *Dactylis glomerata* + *Festuca rubra* floristic type developed on semimurshic arenosol with the higher soil organic matter content of 12.77%, the proportions of valuable grasses were 2.7-fold higher than in the non-irrigated treatment (Figure 1). The proportions of grasses of low economic value, herbs and weeds in meadow sward decreased by 1.5-1.9-fold and 2-fold, respectively. The proportion of short grasses (*Poa pratensis* and *Festuca rubra*) increased, and legumes (*Trifolium pratense* L.*, Trifolium repens* L.*, Lotus corniculatus* and *Medicago lupulina*) persisted, particularly on semimurshic arenosol with the lower content of soil organic matter 5.40% – Figures 1-4, which was highly desirable.

According to Kutera and Czyżyk (1992), and Baryła (2005), wastewater irrigation simplifies the species composition of meadow sward to several valuable grasses, mostly *Dactylis glomerata*, *Poa pratensis* and *Festuca rubra*, while maintaining high sward density. The present results corroborate the previous findings of Grabowski et al. (2008), where it was demonstrated that *Dactylis glomerata* was a persistent and aggressive species able to compete successfully with less competitive sward components. *Festuca rubra* is characterized by low competitiveness, but it is well adapted to a wide range of habitat conditions. The proportion of *Poa pratensis* remained relatively stable throughout the study, which confirms that this species is well suited to wastewater-irrigated grasslands. Another dominant species in the wastewater-irrigated treatment was *Phalaris arundinacea*, which is well adapted to meadow habitats on fertile organic soils with high moisture content.

Talik and Pławiński (1995) found that meadow vegetation grows well in the first years of wastewater irrigation, but later the species composition and density of sward undergo undesirable changes, proportional to the irrigation rates and pollutant loads of wastewater.

The most simplified and floristically impoverished community was *Phalaris arundinacea* + *Glyceria maxima,* located in depressions on semi-murshic arenosol with the higher soil organic matter content of 12.77% – Figures 1-4, and composed of low-quality grasses (351.0 g kg^{-1} DM) and weeds (262.6 g kg^{-1} DM) unsuitable as fodder. Valuable grasses (383.4 g kg^{-1} DM) were represented by species that tolerate moist and very moist habitats: *Phalaris arundinacea*, *Agrostis gigantea* and *Poa palustris*; *Poa pratensis* and *Alopecurus pratensis* were encountered sporadically. The most common grass species of low economic value were: *Glyceria maxima*, *Glyceria fluitans*, *Alopecurus geniculatus*, *Agrostis stolonifera*, *Poa trivialis* and *Deschampsia caespitosa*. Weeds were represented by *Caltha palustris*, *Polygonum bistorta*, *Cirsium palustre*, *Lysimachia nummularia*, *Carex* sp., *Juncus* sp. and others.

According to Talik and Pławiński (1995), grassland irrigation with high quantities of wastewater (800-1000 mm) accelerates sward degradation because grasses sensitive to excess soil moisture are gradually replaced with low-quality grasses and hygrophilous weeds, unsuitable as fodder. As reported by Kutera and Czyżyk (1992), Mikhailova et al. (2000), Čop et al. (2006), Kotlarz et al. (2010), Michaud et al. (2013), Andueza et al. (2016), and Dindová et al. (2019), any transformations in the habitat and land use usually lead to the loss of floristic diversity in grassland communities, which is consistent with the results of this study.

The *Festuca rubra* + *Anthoxanthum odoratum* floristic type, with rich and diverse floristic composition, developed in the control non-irrigated treatment (Figures 1-4). Herbs and weeds (442.3 g kg^{-1} DM), and grasses of low economic importance (283.6 g kg^{-1} DM) predominated in the sward, which was confirmed by the statistical analysis. The proportions of high-quality grasses (213.3 g kg^{-1} DM) and legumes were significantly lower, compared with the irrigated treatment.

Sprinkler irrigation with wastewater, irrespective of the soil type, had a significant effect on the productivity of grassland communities (Figure 5). Depending on the floristic type of a meadow sward, average dry matter yields ranged from 5.4 to 9.4 t ha^{-1} DM, and significantly (1.6-2.8-fold) exceeded the yields in the non-irrigated treatment. Kutera and Czyżyk (1992) observed a steady increase in hay yields in response to wastewater irrigation at an annual dose of 100 - 800 mm. In that study, the highest hay yield (more than 200% higher than in the non-irrigated treatment) was achieved at irrigation doses of 200 - 400 mm.

In the current study, the *Arrhenatherum elatius* floristic type on gleyic arenosol was characterized by the highest productivity (9.4 t ha^{-1} DM). Comparable dry matter yields were harvested in grasslands of the following

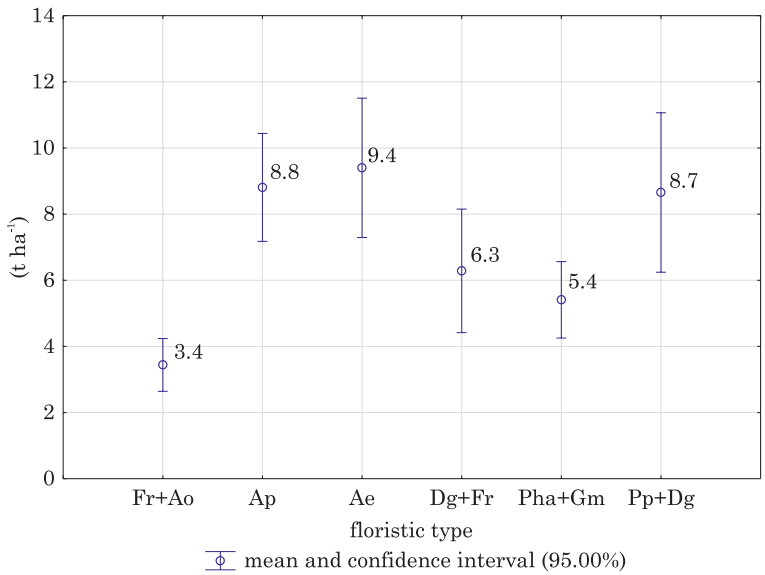

Fig. 5. Yield of dry matter (t ha^{-1}) after 20 years of irrigation (regardless of soil type)

floristic types: *Alopecurus pratensis* (8.8 t ha^{-1} DM) on gleyic arenosol and *Poa pratensis* + *Dactylis glomerata* (8.7 t ha^{-1}DM) on semimurshic arenosol with the higher soil organic matter content of 12.77%. Dry matter yields were lower (6.3 t ha^{-1} DM) in the *Dactylis glomerata* + *Festuca rubra* floristic type on semimurshic arenosol with the lower content of soil organic matter 5.40% (Figure 5).

The lowest yield (1.6 lower than in the non-irrigated treatment) was noted in the degraded *Phalaris arundinacea* + *Glyceria maxima* floristic type (5.4 t ha^{-1} DM) in small local depressions on semimurshic arenosol with the higher soil organic matter content of 12.77% (Figure 5). The findings of Baryła (2005) indicate that in wastewater-irrigated meadows, plants effectively use biogenic elements incorporated into the soil, which has important economic (yield increase) and environmental implications.

In the present study, nutrient content in meadow sward sprinkler irrigated with wastewater was similar in all floristic types (Figures 6-9). Irrespective of the floristic composition of sward, total protein content (134.1-148.8 g kg^{-1} DM) remained within the recommended limits for high--quality fodder (150-170 g kg^{-1} DM) – Nazaruk et al. (2009). The absence of significant differences in total protein content between the analyzed floristic types results primarily from the floristic composition of sward, plant growth stage, the natural trophic status of soil and wastewater irrigation (nitrogen supply), which was observed by Talik and Pławiński (1995), Mikhailova et al. (2000), Čop et al. (2009), Nazaruk et al. (2009), Michaud et al. (2015), Andueza et al. (2016) and Dindová et al. (2019).

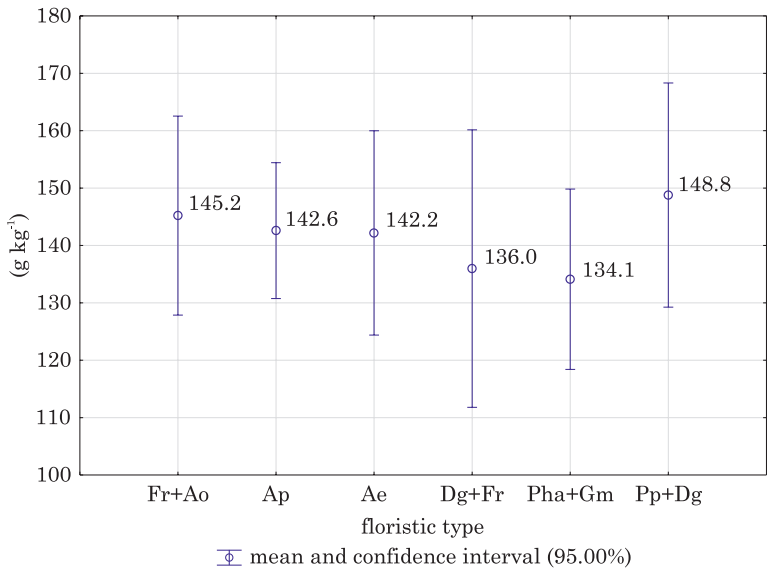

Fig. 6. Mean content of total protein in meadow sward after 20 years of irrigation (regardless of soil type)

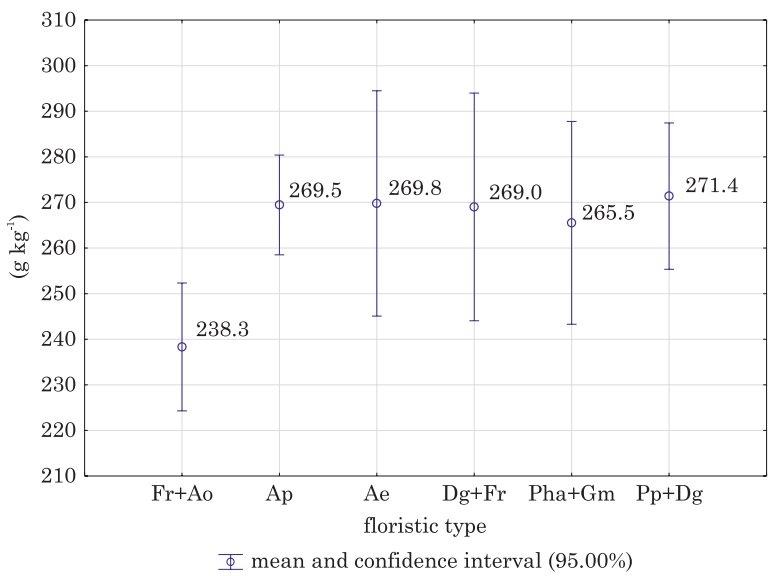

Fig. 7. Mean content of crude fiber in meadow sward after 20 years of irrigation (regardless of soil type)

Average crude fiber content (265.5-271.4 g kg^{-1} DM) did not differ considerably between the analyzed plant communities, particularly in wastewater-irrigated grassland (Figure 7). Significantly higher crude fiber content was observed only in *Alopecurus pratensis* and *Poa pratensis* + *Dactylis*

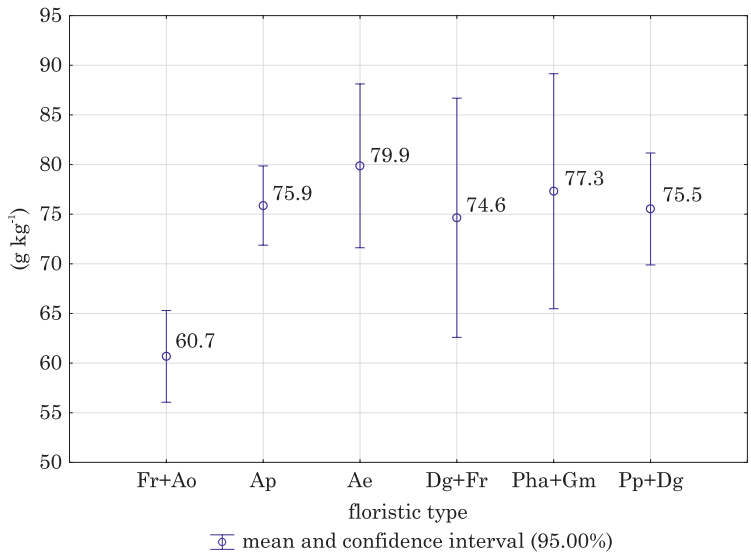

Fig. 8. Mean content of crude ash in meadow sward after 20 years of irrigation (regardless of soil type)

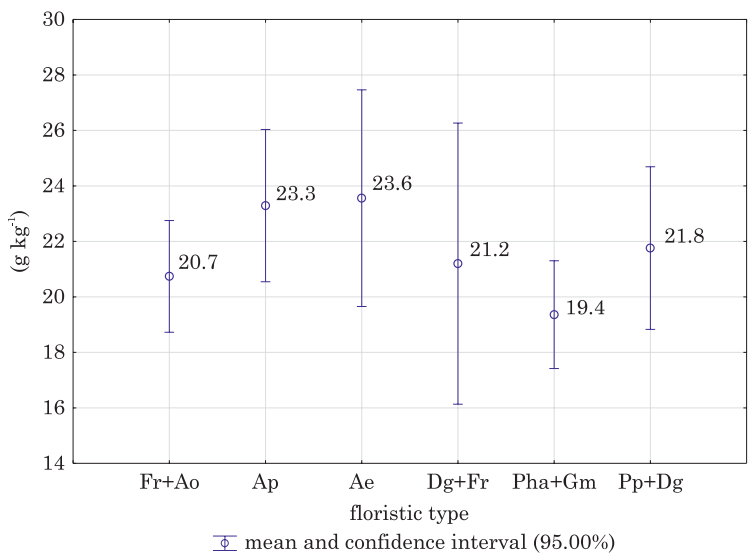

Fig. 9. Mean content of crude fat in meadow sward after 20 years of irrigation (regardless of soil type)

glomerata floristic type, relative to the control treatment. The crude fiber content of meadow sward was optimal for high-quality hay, probably due to the early harvest of first-cut herbage (Mikhailova et al. 2000, Čop et al. 2009, Nazaruk et al. 2009, Grygierzec 2012, Wolański et al. 2015, Andueza et al. 2016, Dindová et al. 2019).

Meadow sward sprinkler irrigated with wastewater had the highest crude ash content (74.6-79.9 g kg^{-1} DM), except for the *Dactylis glomerata* + + *Festuca rubra* community (Figure 8). Significant differences in crude ash content were found between the following communities: *Alopecurus pratensis, Arrhenatherum elatius, Phalaris arundinacea* + *Glyceria maxima* and *Poa pratensis* + *Dactylis glomerata* vs. the *Festuca rubra* + *Anthoxanthum odoratum* community where sprinkler irrigation with wastewater was not applied. Plant communities fertilized with wastewater usually accumulate more crude ash in sward, which was also observed by Grabowski and Bieniek (2004), Arienzo et al. (2009), Römheld and Kirkby (2010) and Andueza et al. (2016).

Throughout the study, the average crude fat content of meadow sward (19.4-23.6 g kg^{-1} DM) was similar in irrigated and non-irrigated treatments, regardless of the floristic composition, which was confirmed by a statistical analysis (Figure 9). According to Nazaruk et al. (2009), the crude fat content of hay is affected mostly by weather conditions as well as the plant development stage at harvest.

CONCLUSIONS

1. Twenty-year sprinkler irrigation of permanent grassland with agri-food industrial wastewater increased the content of phosphorus, potassium, iron, copper, manganese and zinc, and decreased the content of calcium, magnesium and sodium in the analyzed soils. The soil reaction changed from slightly acidic to acidic, and soil salinity remained within the optimal range.

2. The following grassland communities were characterized by the most desirable proportion of valuable grass species of sward: *Alopecurus pratensis* and *Arrhenatherum elatius* developed on gleyic arenosol, *Dactylis glomerata* + *Festuca rubra* community on semimurshic arenosol, and in the *Poa pratensis* + *Dactylis glomerata* community on semimurshic arenosol. The smallest proportion of valuable grass species in sward was observed in the *Phalaris arundinacea* + *Glyceria maxima* community located in depressions on semimurshic arenosol with the higher content of soil organic matter. The *Festuca rubra* + *Anthoxanthum odoratum* community in the non-irrigated treatment was characterized by a low proportion of valuable grass species and high weed infestation.

3. Regardless of the floristic type of sward, the yield of grassland sprinkler irrigated with wastewater was significantly (1.6 to 2.8-fold) higher than the yield of non-irrigated (control) grassland.

4. Hay harvested in wastewater-irrigated meadows met the nutrient requirements of animals in terms of crude fiber, ash and fat, excluding total protein, whose content remained within the recommended limits for high-quality fodder.

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