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Mathematical models use to yield prognosis of perennials on marginal land according to fertilisers doses

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Abstract: Models describe our beliefs about how the world functions. In mathematical modelling, we translate those beliefs into the language of mathematics. Mathematical models can yield prognose on the base of applied fertiliser dose. In this work results of finding yield mathematical model according to fertiliser (nitrogen) dose for perennials (willowleaf sunflower *Helianthus salicifolious*, cup plant *Silphium perfoliatum* and Jerusalem artichoke *Helianthus tuberosus*) on marginal land are presented. Models were described as normalised square equations for dependence between yield and fertiliser doses. Experiments were conducted in lisymeters and vases for willowleaf sunflower and cup plant. For Jerusalem artichoke experiments were done in vases only. All experiments have been doing during two years (2018 and 2019) for different fertilisers doses (45, 90 and 135 kg N·ha^{-1}) in three repetitions. From simulations maximal yield could be achieved for following fertiliser doses – willowleaf sunflower 104 kg N·ha^{-1}, cup plant 85 kg N·ha^{-1} and Jerusalem artichoke 126 kg N·ha^{-1}.

Keywords: biomass, cup plant, fertiliser, Jerusalem artichoke, mathematical modelling, nitrogen, willowleaf sunflower, yield

INTRODUCTION

According to Food and Agriculture Organisation of the United Nations (FAO) the rationalisation of fertiliser use in the developing world is quickly gaining importance [FAO 1973]. Due to this task, researchers have tried to describe biological, technical, social and economic phenomena and processes; as a result, there is a large number of scientific papers that present various mathematical functions, relations and models, with both theoretical and real examples [Hochmuth *et al.* 2011]. With knowledge of mathematical function between fertilising and yield it is possible to choose appropriate fertiliser dose [Kardavut *et al.* 2010]. Fertilisation is one of the soil improvement solutions proposed to compensate for nutrient losses and nutritional deficiencies observed in the production systems [Igue *et al.* 2018]. It affects on environment [Asylbaev *et al.* 2020], cropping costs and crop management [Burzyńska 2019] which factors are important for availability of biomass sources. Within the available biomass sources, there has been an increasing interest in the use of perennial crops [Stolarski *et al.* 2018; 2019a; Varnero *et al.* 2018]. For example these crops can be used as raw material for extraction of biologically active substances [Stolarski *et al.* 2020a] or in bioeconomy for other non-food purposes [Callo-Concha *et al.* 2020; Khawaja *et al.* 2014; Scarlat *et al.* 2015]. The use of lignocellulosic biomass in integrated bio-refineries and second-generation fuel production technologies may develop commercially within a few years [Stolarski *et al.* 2019b]. These crops may be taken into account in a concept of extensive agriculture, especially on marginal soils [Stolarski *et al.* 2019b] to reduce competition for land between biomass implementation in industry and food production [Blanco-Canqui *et al.* 2016]. Marginal lands can be defined as soils that have physical and chemical problems or are uncultivated or adversely affected by climatic conditions. The potential of marginal lands for growing biomass as raw material for bioeconomy has received increased attention in recent years [Blanco-Canqui *et al.* 2016; Krzyżaniak *et al.* 2020; Olba-Zięty *et al.* 2020; Stolarski *et al.* 2020a].

There is an attempt to create a yield forecast system for chosen plants which can be cultivated on marginal land. The system would support potential or present biomass producers in biomass production from marginal land. The system is going to be based on normalised dependencies between yield and fertilisation, water supply to plants, plants density on field or soil type. Normalised dependencies are extracted from regular dependencies by initial pre-treatment procedure which allows to analyse further data. It is expected that data could be described as mathematical functions and would be graphically presented as curves. With knowledge about normalised curves it would be possible to combine similar information about yield dependence from water, plants density or soil type in one yield forecast system. Normalised curves would be suitable to this task due to possibility of investigate each factor influence on yield separately. However estimations of yield dependence from water, plants density or temperature are out of this work scope. In future it is going to be created such system. In practice, crop production forecasts are obtained as the product of two components (1) the estimation of area devoted to a given crop, and (2) the estimation of expected yield per unit of area. While there are no major constraints with the available methodologies for area estimation, forecasting yield is still a major challenge in many countries [AMIS 2020; Delince 2017; Hoefsloot *et al.* 2012; Seghal *et al.* 2002]. The MARS Crop Yield Forecasting System (MCYFS) system was assessed by the performance of forecasts for soft wheat, durum wheat, grain maize, rapeseed, sunflower, potato and sugar beet, and sought [van der Velde, Nisini 2019]. Generally it monitors crop vegetation growth (cereal, oil seed crops, protein crops, sugar beet, potatoes, pastures, rice), including the short-term effects of meteorological events on crop production. It also provides seasonal yield forecasts of key European crops, thereby contributing to the evaluation of global production estimates (wheat, maize, etc.) in support of CAP management decisions [EU Science Hub 2020]. Crop Growth Monitoring and Yield Prediction (B-CGMS) System provides final estimations and predictions of yield and production per agricultural region and per agro-statistical circumscription for winter wheat, winter barley, fodder maize, winter rape, potatoes and sugar beet [Tychon *et al.* 2001]. Other described systems [Basso, Liu 2019] are also focused on typical crops which are traded in huge amounts. There is a gap for yield predicting of other plants as for example cup plant, willowleaf sunflower or Jerusalem artichoke which are suitable for cultivation on marginal land.

STUDY MATERIALS AND METHODS

Three plants were chosen to experiment as follow cup plant (*Silphium perfoliatum*), willowleaf sunflower (*Helianthus salicifolius*) and Jerusalem artichoke (*Helianthus tuberosus*). Two of them (cup plant and willowleaf sunflower) were planted in vases and in lysimeters. Jerusalem artichoke was planted in vases only. Experiments were conducted in two consecutive growing seasons, in 2018 and in 2019 with three N:P:K variants with variant I 45:15:30 kg·ha^{-1}, variant II 90:30:60 kg·ha^{-1} and variant III 135:45:90 kg·ha^{-1}. Experiments were conducted in three repetitions. Each fertiliser dose was applied to three different vases or lysimeters. Vases had diameter 33 cm. Lysimeters had diameter 1 m. Photo 1 presents plants in the experiment.

In 2018 was implemented nitrogen fertilisation by ammonium sulphate (34% N) but in 2019 was implemented ammonium-calcium nitrate (27% N and 2% CaO) as nitrogen fertiliser. In both years was also implemented potassium salt (60% K_2O) and superphospate (40% P_2O_5).

With the assumption that one vase or lysimeter occupy a rectangle with side equal to previously mentioned diameters, the density (D 10^3 plants·ha^{-1}) can be defined as:

$$D = \frac{Va}{Fa} \tag{1}$$

where Fa = 10·10^3 m^2 is the field area as 1 ha but expressed in m^2; Va pcs is the vessel (lysimeter or vase) diameter m^2·plant.

Setting density of vases was 91.83·10^3 plants·ha^{-1} and setting density of lysimeters was 1·10^3 plants·ha^{-1}.

Plants in vases and lysimeters have been treated by the same climatic conditions each year. Each year plants were harvested after growing season and dry matter content was measured. Soil in vases and lysimeters was brown soil developed on sandy rock.

Photo. 1. View of the experimental plantation (photo *M. Strzelczyk*)

A parabola was fitted to each data set related to plant, experiment place (vase or lysimeter) and year. Matlab programme was implemented to finding parabola equations. The general parabola equation can be written as:

$$y = ax^2 + bx + c \tag{2}$$

where y = yield (kg d.m.·vase^{-1} for experiments conducted in vases or kg d.m.·lisimeter^{-1} for experiments conducted in lysimeters), a = quadratic coefficient (kg d.m.·ha^2·vase^{-1}·kg N^{-2} for experiments conducted in vases or kg d.m.·ha^2·lysimeters^{-1}·kg N^{-2} for experiments conducted in lysimeters), b = linear coefficient (kg d.m.·ha·vase^{-1}·kg N^{-1} for experiments conducted in vases or kg d.m.·ha·lysimeter^{-1}·kg N^{-1} for experiments conducted in lysimeters), c = constant (kg d.m.·vase^{-1} for experiments conducted in vases or kg d.m.·lisimeter^{-1} for experiments conducted in lysimeters), x = nitrogen dose (kg N·ha^{-1}).

According to Jadczyszyn [2021] a can be interpreted as coefficient which shows how increase of fertiliser dose by change of one kg will yield increase or decrease (how fast changes yield increase according to fertiliser dose). Coefficient b shows yield increase or decrease per one kg of fertiliser increase. Coefficient c indicates a yield without fertiliser implementation.

For each parabola y_{max} = maximal yield value (kg d.m.·vase^{-1} or kg d.m.·lysimeter^{-1}) was calculated as:

$$y_{\max} = \frac{-b^2 + 4ac}{4a} \tag{3}$$

and adjacent to it of x_{max} = nitrogen dose value value (N kg·ha^{-1}) as:

$$x_{\max} = \frac{-b}{2a} \tag{4}$$

Due to the fact that experimental data were related to different plants densities and years, a normalisation process should be implemented to data [Walesiak 2019] with the aim of data comparison and a general equation calculation [Walesiak 2014]. We do not know kind of data distribution thus data normalisation should be done instead of data standardisation. In our case all data were casted to the range <0; 1> [Peshawa, Faraj 2014; Walesiak 2014]. Proposed solution to data normalisation was based on assumption that if the true minimum of the data set had been used as the minimum value, in this case, the normalised data set would have had values from 0 to 1 even if there had not been a significant difference between minimum and maximum values. Each data was normalised with the use of knowledge about calculated maximal yield by data recalculation of y (kg d.m.·vase^{-1} for experiments conducted in vases or kg d.m. ·lysimeter^{-1} for experiments conducted in lysimeters) on $y_{normalised}$ (dimensionless).

$$y_{\text{normalized}} = \frac{y}{y_{\max}} \tag{5}$$

An average parabola was calculated per plant from all normalised parabolas. The average parabola was normalised at the end. Matlab programme was implemented to finding parabola equations.

Table 1 presents monthly average temperature and average monthly precipitation for years 2018, 2019 and period 1991–2020 [Meteomodel.pl 2020]. Average temperature in 2018 and 2019 was near 2°C higher in compare with average temperature from period 1991–2020. However during vegetation period (IV–X) it was observed that in 2018 average temperature was higher by 2.5°C than for years 1991–2020 and in 2019 by near 1.5°C. Average precipitations were also smaller. There are evidences of climate warming effect.

RESULTS AND DISCUSSION

Table 2 presents yields of plants harvested in vases according to year and nitrogen dose related to yield from vases, standard deviation (*SD*), yield related to ha with *SD*.

Table 3 presents yields of plants harvested in lysimeters according to year and nitrogen dose per lysimeter and recalculated per ha with *SD*.

Presented data from experiments in vases and lysimeters were base for further processing. According to data yields varied and it would be difficult to conclude about yield prognosis without any knowledge about mathematical dependence (a mathematical model expressed by an equation) between nitrogen dose and yield.

Table 1. Monthly average temperatures and precipitations in Wroclaw for years 2018, 2019 and period 1991–2020

Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I–XII	IV–X
	Monthly average temperature (°C)													
2018	3.3	–1.7	1.9	14.0	17.8	19.5	20.8	22.0	16.7	11.4	5.8	3.3	11.2	17.5
2019	0.2	3.8	7.2	11.2	12.4	22.7	20.3	21.2	15.2	11.5	7.6	4.0	11.4	16.4
1991–2020	–0.0	1.1	4.3	9.7	14.3	17.7	19.7	19.3	14.5	9.5	4.7	1.1	9.6	15.0
	Monthly average precipitation (mm)													
2018	12.7	1.6	27.8	31.4	39.8	52.1	82.3	16.6	44.8	33.6	14.6	40.5	397.8	300.6
2019	42.9	26.4	28.5	38.1	60.2	27.2	49.3	44.2	58.4	30.2	33.2	13.9	452.5	307.6
1991–2020	28.3	25.6	35.0	31.2	59.6	65.4	91.4	59.5	48.4	35.8	31.8	28.3	534.7	381.3

Source: Meteomodel.pl [2020].

Table 2. Yields of plants in vases according to year and nitrogen dose

N (kg·ha^{-1})	2018				2019			
	yield	*SD*	yield	*SD*	yield	*SD*	yield	*SD*
	kg d.m.·vase^{-1}		Mg d.m.·ha^{-1}		kg d.m.·vase^{-1}		Mg d.m.·ha^{-1}	
Willowleaf sunflower								
45	0.021	0.002	1.93	0.22	0.037	0.001	3.43	0.11
90	0.046	0.011	4.25	0.77	0.048	0.001	4.38	0.12
135	0.037	0.001	3.37	0.12	0.051	0.001	4.69	0.20
Cup plant								
45	0.030	0.001	2.78	0.12	0.038	0.001	3.49	0.07
90	0.029	0.005	2.63	0.50	0.041	0.003	3.76	0.30
135	0.023	0.002	2.08	0.19	0.028	0.005	2.54	0.44
Jerusalem artichoke								
45	0.048	0.002	4.38	0.19	0.040	0.003	3.64	0.30
90	0.053	0.002	4.87	0.19	0.054	0.005	4.96	0.46
135	0.047	0.003	4.28	0.30	0.059	0.002	5.39	0.19

Source: own study.

Table 3. Yields of plants harvested in lysimeters according to year and nitrogen dose

N (kg·ha^{-1})	2018				2019			
	yield	*SD*	yield	*SD*	yield	*SD*	yield	*SD*
	kg d.m.·lys.$^{-1}$		Mg d.m.·ha^{-1}		kg d.m.·lys.$^{-1}$		Mg d.m.·ha^{-1}	
Willowleaf sunflower								
45	0.95	0.14	9.50	1.37	1.55	0.08	15.47	0.82
90	0.99	0.06	9.90	0.65	1.58	0.07	15.80	0.71
135	0.89	0.03	8.83	0.46	1.29	0.02	12.87	0.25
Cup plant								
45	0.12	0.02	1.17	0.17	0.47	0.03	3.03	1.71
90	0.20	0.02	2.00	0.17	0.46	0.11	4.57	1.07
135	0.18	0.03	1.77	0.25	0.50	0.05	4.98	0.47

Source: own study.

Due to the need to know the exact mathematical model for each plant there were fitted appropriate curves (parabolas).

Table 4 presents parabolas equations fitted to data from experiments according to experiment type (vases or lysimeters), fitted equation, coefficient of determination (R^2), root mean square error (*RMSE*), N dose where maximal yield should appear and maximal yield is calculated from fitted parabola.

Figure 1a presents graphical juxtaposition of all normalised curves for willowleaf sunflower with the aim to better understand and interpret results.

Presented parabola shown that normalised yields for vases were significantly lower in compare with yields from lysimeters for small nitrogen doses. Additionally yields for vases for the first growing period (2018) were smaller for small nitrogen doses for the second growing period (2019). However with the increase of nitrogen doses normalised yield grow faster for the first growing period (2018) than for the second growing period (2019). It was observed a shift between parabolas maximum in 2018 and 2019. For parabola fitted to data from 2019 maximal yield required more nitrogen (169.50 kg·ha^{-1}) than in 2018 (127.25 kg·ha^{-1}).

For yields in lysimeters a little bit different effects were observed but on much smaller scale. For parabola fitted to data from 2018 maximal yield required more nitrogen (87.63 kg·ha^{-1}) than in 2019 (76.95 kg·ha^{-1}). The absolute difference between nitrogen doses for maximal yields in consecutive years for experiments in vases was higher (42.25 kg·ha^{-1}) than for lysimeters (10.68 kg·ha^{-1}). Fitted parabolas to data derived from lysimeters are very close. Fitted parabolas to data derived from vases are less close each to other in compare to those derived from lysimeters. It seems that parabolas for vases constitutes one group

Table 4. Parabolas equations fitted to data from experiments according to experiment type (vases or lisimeters), fitted equation, R^2 coefficient, *RMSE*, N dose where maximal yield should appear and maximal yield is calculated from fitted parabola

Experiment type, year	Equation	R^2	*RMSE*	N (kg·ha^{-1})	Yield max (Mg d.m.·ha^{-1})
Willowleaf sunflower					
Vases, 2018	$y = -0.0002x^2 + 0.0509x + 0.7788$	0.7510	24.65	127.25	4.02
Vases, 2019	$y = -0.0001x^2 + 0.0339x + 2.1855$	0.9795	24.65	169.50	5.06
Lysimeters, 2018	$y = -0.0004x^2 + 0.0701x + 7.1298$	0.6351	24.65	87.63	10.20
Lysimeters, 2019	$y = -0.0011x^2 + 0.1693x + 9.9533$	0.8989	24.65	76.95	16.47
Cup plant					
Vases, 2018	$y = -0.0003x^2 + 0.0413x + 1.2603$	0.7866	24.65	68.83	2.68
Vases, 2019	$y = -0.0004x^2 + 0.0639x + 1.3970$	0.9213	24.65	79.88	3.95
Lysimeters, 2018	$y = -7E\text{–}5x^2 + 0.0206x + 0.5455$	0.7574	24.65	147.14	2.06
Lysimeters, 2019	$y = -0.0003x^2 + 0.0534x + 2.3603$	0.6934	24.65	89.00	4.74
Jerusalem artichoke					
Vases, 2018	$y = -0.0002x^2 + 0.0373x + 3.1933$	0.8805	24.65	93.25	4.93
Vases, 2019	$y = -0.0001x^2 + 0.0432x + 2.0763$	0.9459	24.65	216.00	6.74

Explanations: R^2 = coefficient of determination, *RMSE* = root mean square error, y = yield (Mg d.m.·ha^{-1}), x = nitrogen dose (kg N·ha^{-1}).

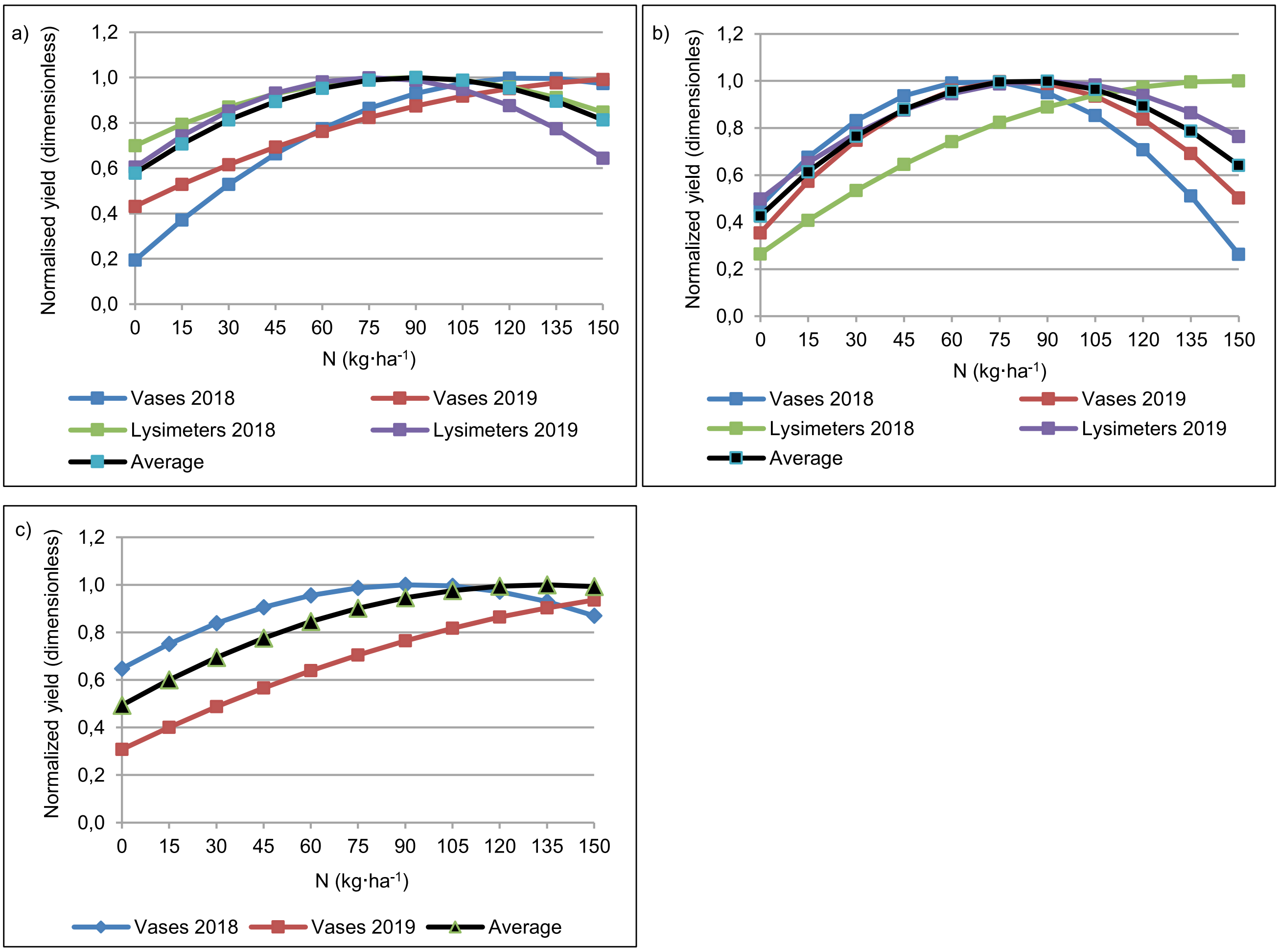

Fig. 1. Curves of normalised yields together with an average normalised yield derived from all experiments for; a) willowleaf sunflower, b) cup plant, c) Jerusalem artichoke; source: own study

and parabolas for lysimeters constitutes second group. An average parabola is between the two groups.

Figure 1b presents graphical juxtaposition for cup plant. Fitted parabolas for data derived from experiments in vases are close each to other. However one parabola derived from data from lysimeters, from 2018 is somehow separate from others. Its maximum value falls for 147.14 kg N·ha^{-1} dose. For other parabolas maxims falls as follows doses 68.83 kg N·ha^{-1} (for vases in 2018), 79.88 kg N·ha^{-1} (for vases in 2019) and 89.00 kg N·ha^{-1} (for lysimeters in 2019). These maximal values are relatively close to each other.

Figure 1c presents graphically results for Jerusalem artichoke. Maximal values fall for very different nitrogen doses. For parabola derived from experiments conducted in vases, in 2018 maximum falls for 93.25 kg N·ha^{-1} dose. But in 2019 it falls for 216.00 kg N·ha^{-1} dose.

Table 5 presents average normalised yield equations for calculated for each plant with goodness of fit parameters and calculated nitrogen dose (as x_{max}), for maximum yield. There are included nitrogen doses for which fitted average parabolas reached their maxims. The smallest nitrogen dose was for 85 kg N·ha^{-1}, for cup plant. The next was for willowleaf sunflower, for 104 kg N·ha^{-1}. The biggest one was for Jerusalem artichoke, for 126 kg N·ha^{-1}.

Table 5. Average normalised yield equations for calculated for each plant with goodness of fit parameters and calculated nitrogen dose for maximum yield

Parameter	Willowleaf sunflower – normalised yield from vases and lysimeters	Cup plant – normalised yield from vases and lysimeters	Jerusalem artichoke – normalised yield from vases
Linear model Poly2: $f(x) = ax^2 + bx + c$			
a	−4.388E−5	−7.762E−5	−2.77E−5
b	0.009128	0.01321	0.006988
c	0.482200	0.39670	0.477900
SSE	0.8504	1.008	0.5553
R^2	0.6085	0.6293	0.5328
Adjusted R^2	0.5957	0.6172	0.5005
$RMSE$	0.1181	0.1286	0.1384
x_{max}	104	85	126

Explanations: a, b, c = coefficients (with 95% confidence bounds), SSE = sum of squared errors, R^2 = coefficient of determination, $RMSE$ = root mean square error, x_{max} = nitrogen dose (kg·ha^{-1}) for maximum yield.
Source: own study.

For all plants, the calculated values of nitrogen doses differed depending on the type of experiment (vases, lysimeters) and the year of the experiment. Evidence of average temperatures and precipitations during 2018 and 2019 analysed on the background 1991–2020 shown climate changes and its rapid warming in Poland. They have influenced on yield levels from conducted experiments in lysimeters and vases.

- **Willowleaf sunflower – normalised data.**

Data normalisation process allows to compare results obtained in different conditions. For willowleaf sunflower normalised yield without fertilisation was changing from 20% in 2018 to 43% of maximal yield for plants grown in vases, in 2019. For plants grown in lysimeters normalised yield without fertilisation varied from 60% in 2019 to 70% in 2018. Yields were significantly higher for plants grown in lysimeters in compare with plants grown in vases. Big changes occurred between normalised yield without fertilisation for plants grown in vases and plants grown in lysimeters. Normalised yields of plants grown in lysimetrs without fertilising were near three times higher than plants grown in vases. It could be explained that plants grown in lysimeters had better growing conditions (bigger available soil volume per one plant) in compare with plants grown in vases. Plants grown in lysimeters also had smaller variation of normalised yield between years (60–70%) than plants grown in lysimeters (20–43%). It reflected on average normalised yield calculated from all data related to sunflower which was on the level 48%. Vases contained significantly smaller soil volume in compare with soil volume, in lysimeters. Thus plants in vases had smaller amount of nutrients which were needed to plants growth. It reflected on the level of normalised yields in vases without fertilisation. Normalised yields without fertilisation were higher in the first year of experiments (2018) in compare with the second year (2019) or similar fertiliser doses. In the second year of experiments, plants were grown in the same vases, in the same soil conditions. For the case when there were no fertilisation, plants took nutrients from soil only. Year after year nutrients were exhausted from soil and it specially reflected on normalised yield without fertilisation. Graphical representation of normalised curves for lysimeters shows that normalised yield required more fertilisation in the second year for achieving the same normalised yield level as in the first year. Maximal predicted yield for plants grown in vases was for higher dose of fertilisation level (169.5 kg N·ha^{-1}) in the second year of experiments (2019) than in the first year (2018, 127.25 kg N·ha^{-1}). During experiments it was observed much more bigger roots volume at the second year of experiments (2019) in compare with the first year of experiments (2018) both for plants grown in vases and in lysimeters. Plants extended roots amount and volume, and used more intensively nutrients in the second year of experiments in compare with the first year. For plants grown in vases it led to near complete exhaustion of nutrients at the second year of experiments. It was reflected on normalised yield curves. This phenomenon occurred also for plants grown in lysimeters in smaller scale but with maintaining similar effects sequence.

- **Willowleaf sunflower – yield equations.**

For data from vases in the case of willowleaf sunflower, the maximum yield was calculated for a nitrogen dose of about 127 kg·ha^{-1} and it amounted to 4.02 Mg d.m.·ha^{-1} for 2018. In 2019, the calculated maximum was for a nitrogen dose of 170 kg N·ha^{-1} and it amounted to 5.06 Mg d.m.·ha^{-1}. The nitrogen dose increased year on year by 40 kg N·ha^{-1} for the maximum yield. The calculated maximum yield increased by about 1 Mg d.m.·ha^{-1} year to year for willowleaf sunflower, as the root ball grew larger, absorbed more nitrogen and produced higher yields. In the case of experiments carried out in lysimeters, the calculated maximum yield was for 87.6 kg N·ha^{-1} and amounted to 10.2 Mg d.m.·ha^{-1} in 2018. In 2019, the calculated maximum for 76.95 kg N·ha^{-1} was 16.47 Mg d.m.·ha^{-1}. The calculated nitrogen dose for obtaining the maximum yield decreased by about 10 kg N·ha^{-1} with its increase by about 6 Mg d.m.·ha^{-1}. Presumably, mineralisation of plant debris and migration of nitrogen compounds from these debris to the soil took place here. This is due to the larger volume of lysimeters compared to the volume of vases and the absorption of nutrients from the volume of soil contained in the vessels. Also it can be related to the estimated planting density per hectare (91,827 thous. plants per ha for vases and 10,000 thous. plants per ha for lysimeters). Planting the plants too densely causes the soil to deplete nutrients more quickly and reduces the yield. Plants do not have enough nutrients for higher yield production. Average from three years willowleaf yield [Stolarski *et al.* 2017] on field experiment was 8.7 Mg d.m.·ha^{-1} without any fertilisation, 9.8 Mg d.m.·ha^{-1} for 85.0 kg N·ha^{-1} and 10.4 Mg d.m.·ha^{-1} for 170.0 kg N·ha^{-1}. Reported plants density was 10.0 thous. plants per ha. Differences between yields from lysimeters and from field can be explained by fact that experiments in lysimeters were conducted only by two consecutive years while field experiments were conducted by three consecutive years in quite different place, weather conditions and nitrogen dose. However yields harvested from lysimeters increased year to year. In other field experiment willofleaf yield reached 6.2 Mg s.m.·ha^{-1} in the first year and 16.5 Mg s.m.·ha^{-1} [Mudryk, Wróbel 2012]. Plants density was related to 4 thous. plants per ha, NPK mineral fertilisation 50:40:150 kg·ha^{-1}. Authors of the experimented underlined that the obtained yield was relatively high (especially in the second year), however it would be difficult to repeat in normal, big scale crop.

- **Willowleaf sunflower – results in relation to literature.**

For data from vases in the case of willowleaf sunflower, the maximum yield was calculated for a nitrogen dose of about 127 kg·ha^{-1} and it amounted to 4.02 Mg d.m.·ha^{-1} for 2018. In 2019, the calculated maximum was for a nitrogen dose of 170 kg N·ha^{-1} and it amounted to 5.06 Mg d.m.·ha^{-1}. The nitrogen dose increased year on year by 40 kg N·ha^{-1} for the maximum yield. The calculated maximum yield increased by about 1 Mg d.m.·ha^{-1} year to year for willowleaf sunflower, as the root ball grew larger, absorbed more nitrogen and produced higher yields. In the case of experiments carried out in lysimeters, the calculated maximum yield was for 87.6 kg N·ha^{-1} and amounted to 10.2 Mg d.m.·ha^{-1} in 2018. In 2019, the calculated maximum for 76.95 kg N·ha^{-1} was 16.47 Mg d.m.·ha^{-1}. The calculated nitrogen dose for obtaining the maximum yield decreased by about 10 kg N·ha^{-1} with its increase by about 6 Mg d.m.·ha^{-1}. Presumably, mineralisation of plant debris and migration of nitrogen compounds from these debris to the soil took place here. This is due to the larger volume of lysimeters compared to the volume of vases and the absorption of nutrients from the volume of soil contained in the vessels. Also it can be related to the estimated planting density per hectare (91,827 thous. plants per ha for vases and 10,000 thous. plants per ha for lysimeters). Planting the plants too densely causes the soil to deplete nutrients more quickly and reduces the yield. Plants do not have enough nutrients for higher yield production. Average from three years willowleaf yield [Stolarski *et al.* 2017] on field experiment was 8.7 Mg d.m.·ha^{-1} without any fertilisation, 9.8 Mg d.m.·ha^{-1} for 85.0 kg N·ha^{-1} and 10.4 Mg d.m.·ha^{-1} for 170.0 kg N·ha^{-1}. Reported plants density was 10.0 thous. plants per ha. Differences between yields from lysimeters and from field can be explained by fact that experiments in lysimeters were conducted only by two consecutive years while field experiments were conducted by three consecutive years in quite different place, weather conditions and nitrogen dose. However yields harvested from lysimeters increased year to year. In other field experiment willofleaf yield reached 6.2 Mg s.m.·ha^{-1} in the first year and 16.5 Mg s.m.·ha^{-1} [Mudryk, Wróbel 2012]. Plants density was related to 4 thous. plants per ha, NPK mineral fertilisation 50:40:150 kg·ha^{-1}. Authors of the experimented underlined that the obtained yield was relatively high (especially in the second year), however it would be difficult to repeat in normal, big scale crop.

- **Cup plant – normalised data.**

For cup plant normalised yield without fertilisation was 47% in 2018 and 38% of maximal yield for plants grown in vases, in 2019 (near 0.8 times less than in 2018). For plants grown in lysimeters normalised yield without fertilisation varied from 25% in 2018 to 50% in 2019 (2 times more than in 2018). There was not so clear situation in compare with willowleaf sunflower. Normalised yield without fertiliser was smaller for experiments conducted in vases in the second year of experiment in compare with the first year. It was far from expectations. There could occurred an unpredicted and indefinite phenomenon which influenced on normalised yield in vases. Normalised yields for experiments conducted in lysimeters kept expectations. The normalised yield was lower at the first year of experiments in compare with the second year. All explanations about year-by-year root system development, soil volume and better nutrients uptake were valid similarly as for willowleaf sunflower. Graphical representation of normalised curves for vases shows that normalised yield required more fertilisation in the second year for achieving the same normalised yield level as in the first year. Maximal predicted yield for plants grown in vases was for higher dose of fertilisation level (79.88 kg N·ha^{-1}) in the second year of experiments (2019) than in the first year (2018, 68.83 kg N·ha^{-1}). It was opposite effect in compare with experiments conducted in lysimeters. There was maximal predicted yield for smaller dose of fertilisation level (89.00 kg N·ha^{-1}) in the second year of experiments (2019) than in the first year (147.14 kg N·ha^{-1}).

- **Cup plant – yield equations.**

Yield equations had quadratic coefficients smaller than 0 in all cases. Explanation of this fact was given in the section related to willowleaf sunflower. Quadratic coefficients of yields equations derived from experiments conducted in vases, in 2018 were equal to –0.0003 Mg d.m. ha·kg^{-2} and were closer to 0 value than for year 2019 (–0.0004 Mg d.m. ha·kg^{-2} – 1.3 times more than in 2018). The yield equation for vases experiments in 2018 was closer to linear dependence between yield and fertilisation than in 2019. Similar situation occurred for experiments conducted in lysimeters. The quadratic coefficient were closer to 0 value for year 2018 (–0.00007 Mg d.m. ha·kg^{-2}, 4.3 times less than for vases in 2018, 5.7 times less than for vases in 2019) than in 2019 (–0.0003 Mg d.m. ha·kg^{-2}, 4.3 times more than for lysimeters in 2018, the same as for vases in 2018, 1.3 times less for than for vases in 2018). Generally quadratic coefficients were similar each to other with the exception of the quadratic coefficient for experiments conducted in lysimeters in 2018 which was significantly lower than other coefficients.

For cup plant all linear coefficients had positive value. They described how much adding one kg·ha^{-1} of fertiliser can yield increase in Mg d.m.·ha^{-1}. For experiments conducted in vases, in 2018 it was 0.0413 Mg d.m.·ha^{-1}·kg^{-1}. For experiments conducted in vases, in 2019 it was 0.0639 Mg d.m.·ha^{-1}·kg^{-1} (near 1.5 more than for vases in 2018). For experiments conducted in lysimeters, in 2018, it was 0.0206 Mg d.m.·ha^{-1}·kg^{-1} (2 times more than for vases in 2018, near 3 times more than for vases in 2019). For experiments conducted in lysimeters, in 2019, it was 0.0534 Mg d.m.·ha^{-1}·kg^{-1} (2.6 times more than for lysimeters in 2018, 1.3 times more than for vases in 2018, 1.2 times less than for vases in 2019). Linear coefficients have shown growing trend year to year for similar vessels (vases or lysimeters).

The constant coefficient was equal to 1.2603 Mg d.m.·ha^{-1} for experiments conducted in vases, in 2018. For experiments conducted in vases, in 2019 it was 1.3970 Mg d.m.·ha^{-1} (1.1 times more than for vases in 2018). For experiments conducted in lysimeters, in 2018, it was 0.5455 Mg d.m.·ha^{-1} (2.3 times less than for vases in 2018, 2.6 times less than for vases in 2019). For experiments conducted in lysimeters, in 2019, it was 2.3603 Mg d.m.·ha^{-1} (4.3 times more than for lysimeters in 2018, 1.9 times more than for vases in 2018, 1.7 times less than for vases in 2019). Coefficients for vases are very similar. However coefficients for lysimeters show big difference among year 2018 and year 2019.

- **Cup plant – results in relation to literature.**

In 2018, the calculated maximum yield was 2.68 Mg d.m. ·ha^{-1} for 68.83 kg N·ha^{-1}, for vases. In the following year it was higher and amounted to 3.95 Mg d.m.·ha^{-1} for 79.88 kg N·ha^{-1}. There was an increase in the maximum yield by about 1 Mg d.m. ·ha^{-1} with an increase in fertilisation by about 11 kg N·ha^{-1}. However, in the case of lysimeters, the calculated maximum yield was 2.06 Mg d.m.·ha^{-1} for 147.14 kg N·ha^{-1} in 2018. In 2019, the calculated maximum yield was 4.74 Mg d.m.·ha^{-1} for 89.00 kg N·ha^{-1}. A higher yield occurred at a lower dose of fertiliser in 2019 compared to 2018. The same factors were at work here as for willowleaf sunflower. Bury *et al.* [2020] reported that the collected dry mass yield of cup plant significantly differed between the years and methods of establishing the plantation. The biomass yields increased in the first two years of full vegetation from 9.3 to 18.1 Mg d.m.·ha^{-1}·y^{-1}, and then decreased in the third year of vegetation to ca. 13 Mg d.m.·ha^{-1}·y^{-1} because of drought. Significantly higher d.m. yield was obtained by sowing seeds (ca. 13.9 Mg d.m.·ha^{-1}·y^{-1}) compared to the planting method (ca. 13.0 Mg d.m.·ha^{-1}·y^{-1}), due to the higher plant density obtained after the sowing method compared to the planting method [Bury *et al.* 2020]. Plant density for sowing seeds varied from 6.38 to 14.75 thous. plants per ha. Plant density for planting varied from 4.23 to 4.40 thous. plants per ha. In both cases all the time was implemented the same mineral fertilisation (100 kg N·ha^{-1}, 35 kg P·ha^{-1}, 110 kg K·ha^{-1}). A series of studies was conducted to evaluate the adaptation and productivity of cup-plant across a range of following factors plant densities (104,000–208,000 plants per ha), cutting stages (early vegetative to seed formation), and different levels of N (0–400 kg N·ha^{-1}) and P (0–400 kg P_2O_5·ha^{-1}) fertilisation [Pichard 2012]. They show annual DM yield variation from 9.6 to 22.3 Mg d.m.·ha^{-1} for the two harvest years according to different factors combination.

Different authors reports following yields 10.8 Mg d.m.·ha^{-1} [Schittenhelm *et al.* 2016], 11.2–13.9 Mg d.m.·ha^{-1} [Stolarski 2004], 8.4–14.3 Mg d.m.·ha^{-1} [Wever *et al.* 2019].

- **Jerusalem artichoke – normalised data.**

Jerusalem artichoke was examined only in vases where only the yield of the aerial part was examined. The normalised yield without fertilisation was 65% in 2018 and 27% of maximal yield for plants grown in vases, in 2019 (2.4 times less than in 2018). It was in accordance with experiments results observed for willowleaf sunflower and cup plant which were conducted in vases. The same explanations as given for willowleaf sunflower there would be valid. In 2018, the calculated maximum yield was 4.94 Mg d.m.·ha^{-1} for 93.25 kg N·ha^{-1}. In 2019, the calculated maximum yield was higher by about 2 Mg d.m.·ha^{-1} and amounted to 6.74 Mg d.m. ·ha^{-1} with about 2.3 times higher fertiliser dose of 216.00 kg N·ha^{-1} (increase of the dose fertiliser by 122.75 kg N·ha^{-1} year by year). Such a large increase in nitrogen consumption resulted from the plant's need to produce tubers underground.

- **Jerusalem artichoke – yield equations.**

Yield equations had quadratic coefficients smaller than 0 in all cases. Explanation of this fact was given in the section related to willowleaf sunflower. Quadratic coefficients of yields equations derived from experiments conducted in vases, in 2018 were equal to –0.0002 Mg d.m. ha·kg^{-2}. Closer to 0 value were results for year 2019 (–0.0001 Mg d.m. ha·kg^{-2} – 2 times less than in 2018). The yield equation for vases experiments in 2019 was closer to linear dependence between yield and fertilisation than in 2018.

For Jerusalem artichoke all linear coefficients had positive value. The coefficient for 2018 was 0.0373 Mg d.m.·ha^{-1}·kg^{-1}. In 2019 it was 0.0432 Mg d.m.·ha^{-1}·kg^{-1} (1.6 more than in previous year). It increased year by year.

For 2018 constant coefficient was 3.1933 Mg d.m.·ha^{-1}. It was 1.5 times less when it decreased to 2.0763 Mg d.m.·ha^{-1} for experiments in 2019. It was quite different trend in compare with experiments conducted in vases for willowleaf sunflower and cup plant. There could occur an undefined and unexpected phenomenon.

- **Jerusalem artichoke – results in relation to literature.**

According to reported results from other field experiment, an average yield from three consecutive years of Jerusalem artichoke cultivation was 4.0 Mg d.m.·ha^{-1} without any fertilisation, 5.8 Mg d.m.·ha^{-1} for 85 kg N·ha^{-1} and 6.5 Mg d.m.·ha^{-1} for 170 kg N·ha^{-1} [Stolarski *et al.* 2017]. In this experiment Jerusalem artichoke was planted with the density of 20 thous. plants per ha. The differences between yields in vases and yields on the experimental field can be explained by significant difference in density of plants (91.83 thous. plants per ha for vases and 20 thous. plants per ha for field experiment). Kays and Nottingham [2007] reported that the dry matter yield of the aboveground parts of Jerusalem artichoke ranges from 4 to 30 Mg d.m.·ha^{-1}, depending on the genotype, climatic conditions, soil type and plantation age. Szpunar-Krok *et al.* [2016] harvested an average yield 9.79 Mg d.m.·ha^{-1} of the aboveground parts of Jerusalem artichoke (stems and leaves) in over the 3-year research period. The harvest was carried on a soil of a good rye complex, class IVb (according to Polish soil classification) with acidic reaction. The average yield was higher than 8.58 Mg d.m.·ha^{-1} reported by Sawicka and Skiba [2009] on a soil of good rye complex (according to Polish soil classification) and close to other authors 9.5 Mg d.m.·ha^{-1} on a light soil [Kuś *et al.* 2008], 9.10–12.1 Mg d.m.·ha^{-1} with fertilisation by the sludge [Kowalczyk-Juśko 2010].

CONCLUSIONS

The knowledge of the dependence of nitrogen doses and the yields dependent on them is important for the proper management of the plantation, the selection of nitrogen fertiliser doses and the reduction of the amount of pollutants entering the groundwater from fertilisers [SERAFIN *et al.* 2020; WIDELSKA, WALCZAK 2019]. Climate changes (climate warming) had strong impact on plants conditions during experiments in lysimeters and vases. Normalised yield curves could help to diminish this impact in data analysis. The current study analysed the possibility of mathematical models use to yield prognosis of perennials on marginal land according to fertilisers doses with positive effect. Proper fertilisers doses (especially for nitrogen fertiliser) can be a one from many factors which could reduce crops impact on environment due to emissions reduction from agriculture. Smaller emissions from agriculture are desirable due to limitation of climate changes and especially climate warming.

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