Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

The impact of buckwheat and paulownia (Paulownia elongata x P. fortunei) intercropping on beekeeping value and buckwheat yield

Paweł Chorbiński
Wroclaw University of Environmental and Life Sciences
Marek Liszewski
marek.liszewski@upwr.edu.pl
Wroclaw University of Environmental and Life Sciences
Przemysław Bąbalewski
Wroclaw University of Environmental and Life Sciences
Anna Jama-Rodzeńska
Wroclaw University of Environmental and Life Sciences

Article

Keywords: agroforestry, beekeeping value, buckwheat, paulownia, sugar mass, nectar mass

Posted Date: April 29th, 2024

DOI: https://doi.org/10.21203/rs.3.rs-4176722/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Scientific Reports on September 14th, 2024. See the published version at https://doi.org/10.1038/s41598-024-72493-x.

Abstract

Increasing crop diversity is a way for agriculture to transition towards a more sustainable and biodiversity-friendly system. Growing buckwheat intercropped with paulownia can contribute not only to mitigating climate change but can also enrich the environment with species of agricultural importance, without causing a decline in pollinators, since buckwheat is pollinated mainly by the honeybee. Buckwheat is a significant forage crop in some areas. In a field experiment comparing growing buckwheat with paulownia against a monoculture crop, we investigated differences in flower visitation and beekeeping value, as well as the associated impact on crop yields. We analysed the effect of intercropping on the beekeeping value of buckwheat in terms of bee population size and the sugar mass in buckwheat flowers, nectar mass in buckwheat flowers, the quality of the delivered raw sugar and biometric characteristics. We found significant differences in the number of branches on the main shoot and the total number of branches. Significantly higher parameters were obtained in sites with buckwheat monoculture. We recorded more flowers per plant per observation day and more flowers in million flowers per hectare per observation day in the intercropping of buckwheat with paulownia. Based on our experiment, we concluded that growing buckwheat in monoculture significantly increased the number of flowers, resulting in an increase in pollinator density and an increased number of pollinators per unit area.

INTRODUCTION

Climate warming, global population growth and loss of biodiversity are urgent global issues that require action to transform agriculture for it to take a more sustainable direction.[1−3] The panacea for these changes has been seen in crop diversification and the fostering of agrobiodiversity.[4−7] Higher levels of crop diversity can be achieved through intercropping.[8,9] In intercropping, two or more plant species are grown on the same field at the same time. A particular form of intercropping is strip cropping (alley cropping),[10] used instead of monocultures, which encourage the mass development of agrophages and lead to nutrient depletion and an increase in the abundance of certain weed species. The intercropping system allows the soil to be protected from erosion, excessive drying, enables pest reduction and reduces the presence of some weeds.[11]

Intercropping that involves melliferous plants protects pollinators, since lack of floral resources in modern agricultural landscapes is considered to be a major factor driving pollinator decline.[12,13] Growing flowering plants in other plants' systems can be a way to improve farmland biodiversity.[14,15] Intercropping of trees and melliferous plants increases the biodiversity of the agroecosystem while allowing farms to generate additional income, promoting the development of biological life in the soil, reducing water losses, preventing nitrogen leakage from mineral fertilisers in the soil profile.[11]

The development of agroforestry systems under conditions that obtain in Poland seems particularly important in the context of mitigation of the negative effects of climate change, vast areas of marginal land, and a growing demand for bioenergy and organic produce. Strip-tree intercropping has the advantage of favourable shading, which indirectly contributes to increasing water retention, as paulownia trees have large leaves and the ability to store water. Inter-row shading by paulownia trees can protect the melliferous plants from too much sunlight exposure during the flowering period and thus prevent decline in nectar secretion (desiccation of nectar). Nectar desiccation results in flowers becoming less attractive to pollinating insects, which leads to a decrease in seed yield.[16,17]

Three-quarters of our global crops depend in part on insect pollination necessary for yield, making pollinator management an essential part of their agricultural management.[18] Common buckwheat (*Fagopyrum esculentum* Moench) is a reliable and highly productive melliferous plant[19]. Large number of flowers that bloom over a long period contributes to making buckwheat fields a valuable and suitable site for bees.[16] Buckwheat honey is highly valued by professionals (nutritionists, doctors) - due to its specific organoleptic properties, such as its distinctive colour, pungent taste and molasses aroma - but is less favoured by consumers.[20] Regardless of the consumer's preferences, buckwheat honey has a very high nutritional value, paired with beneficial antioxidant and anti-inflammatory effects.[21,22] Buckwheat is thus an important melliferous crop from a beekeeping point of view, which in favourable conditions can generate significant quantities of honey. Buckwheat nectar production can amount to 50 to 100 kilograms of honey per hectare, which is due to the extended flowering period of over 30 days.[23] Depending on the buckwheat variety, growing conditions and climate, nectar production can range from 6 up to 362 kg·ha^{-1}, and for the very best varieties can reach 15–300 kg·ha^{-1} [24–27]. During its growth, over 2–3 months, a single buckwheat plant can develop 500–2000 flowers, each of which can potentially produce from 0,05 to 10 µl of nectar.[27] It has been found that a single foraging trip on buckwheat flowers can increase plant productivity by 25–30%[28], three to four foraging trips are sufficient to pollinate one buckwheat flower, while a bee visiting more than five times reduces the productivity of the plant.[28]

Buckwheat nectar contains sugars, mainly hexoses (glucose and fructose), sucrose, vitamins and amino acids.[29, 30] Concentration of sugars in the nectar is variable and depends on the time of day, ranging from 8 to 35%, though it may reach 51%.[24,30–32] Nectar production is sensitive to environmental stresses such as light deficiency, water stress and low temperature.[33] High temperatures and drought significantly reduce the amount of nectar produced by the plant, by up to 15 times, though the concentration of sugar in the nectar in such situation increases.[32] Despite high concentration of sugars in the nectar, the attractiveness of buckwheat for pollinators under these conditions decreases, because the nectar dries out quickly in the nectaries, reducing its accessibility.[31] According to Taylor and Obendorf (2001),[34] as well as Halbrecq et al. (2005)[35] he production of nectar and the setting of buckwheat seeds depend on the position of the inflorescences in the cluster, which is related to their access to assimilates.

Nectariferous paulownia flowers are a rich source of nutritious honey.[36] In 2015, a new fast-growing tree was introduced into cultivation in Poland, under the commercial name Oxytree (Clon in Vitro 112). Paulownia Clon In Vitro 112 is a tree created in laboratory conditions by crossing and cloning two species: *Paulownia elongata* and *P. fortunei*. The Oxytree hybrid is characterised by rapid vegetative growth and is considered suitable for roundwood and biomass production and for revegetation. According to the producer, Oxytree can yield up to 700 kg of honey per ha of crop.[37]

There is not much data regarding evaluation of buckwheat intercropped with paulownia in terms of their beekeeping value. To the authors' knowledge, there have been no such studies in Poland nor worldwide. In formulation our research hypothesis, we assumed that intercropping buckwheat and paulownia would result in favourable changes in the beekeeping value of buckwheat, and an increase in the number of visiting bees. The aim of the study was to determine the feasibility of growing paulownia and buckwheat (in the interrows between the trees) in the same field. Moreover, we investigated the beekeeping value of buckwheat grown in an alley

system in terms of: the quantities of secreted nectar, sugar mass per 10 buckwheat flowers and per unit area (ha), as well as the potential raw sugar availability for bees.

METHODS

Study system

A rigorous field experiment using the randomised block method including buckwheat (*Fagopyrum esculentum* Moench) and paulownia (Clon in Vitro 112 – Oxytree; *P. elongata* × *P. fortunei*) has been set up in 2019 at the Research and Education Station of the Wrocław University of Environmental and Life Sciences (51°07'00"N; 17°10E, 121 above sea level). The factor under study was the intercropping of buckwheat between paulownia trees (AP). The experimental design included control sites (AK), i.e. buckwheat plots grown without paulownia. The buckwheat experiment ran from 2021 to 2023 and included five replicates. OXYTREE seedlings were planted on 30.05.2019. In spring, on 19.05.2020, we carried out technical pruning to promote stem growth (future trunk). Buckwheat of the Kora variety was sown on 11.05.2021, 04.05.2022 and 20.04.2023 at a density of 250 seeds per square metre. The area of the buckwheat plot covered 30 square metres. The trees were planted in rows of five, the row spacing within the field was 5m and the spacing between the trees in a row 4m. The density of tree spacing was thus typical for Oxytree roundwood cultivation.

Soil conditions

Our rigorous field experiment was based on soil classified as humic ordinary alluvial soils (Type Ordinary alluvial soils - Polish Soil Classification (SGP6): SF), Subtype: humic ordinary alluvial soils - Polish Soil Classification (SGP6): SFh). The soil was classified as class F-IV b-a.[38] Soil samples for bioavailable forms of macronutrients (P, K, Mg) and mineral nitrogen analysis were procured prior to sowing buckwheat from several randomly selected locations within the field, separately for each site to obtain an average sample. Soil was sampled from the 0–30 cm layer using a soil sampler tool, air-dried, ground with a porcelain pestle and mortar, and sieved to < 2 mm. A portion of each sample was then finely ground for analysis. Soil testing included: determination of basic soil characteristics and properties, such as soil morphology, systematic position, use value, pH, macronutrient content, including mineral nitrogen content.

We carried out characterisation of the following soil properties:

- content of bioavailable forms of P, K, Mg and Ca - using the Egner-Riehm method
- available magnesium content - using Schachtschabel method,
- pH in distilled water and in 1M KCl - using potentiometric pH metres,
- nitrogen content - using the modified Kjehdal method (total nitrogen determination).

The soil pH in both the intercropped site and the control site was slightly acidic both before the experiment had been set up and at the end of the study period. Phosphorus and potassium contents on both sites were very high in the year the experiment started and at the end of the study period - phosphorus level was high (AK) and very high (AP). Towards the end of the 2023 season, the potassium content was found to be reduced to ‘high’ (AK). The magnesium content was very high in the soil in both sites in the year the experiment started, while by the end of 2023, it had decreased to medium (Table 1). Over time, the mineral nitrogen content in the soil decreased.

Table 1
Soil pH and macro-element content of the soil profile (0–30 cm) in 2019 and 2023.

Detailed determination	2019		2023	
	AK	AP	AK	AP
pH in KCl (soil pH)	6.2 (slightly acidic)	5.8 (slightly acidic)	5.8 (slightly acidic)	5.9 (slightly acidic)
Phosphorus P_2O_5 (mg/100 g of soil)	48.5 (very high)	27.6 (very high)	18.7 (high)	22.9 (very high)
Potassium K_2O (mg/100 g gleby)	33.5 (very high)	33.5 (very high)	22.3 (high)	25.9 (very high)
Magnesium Mg (mg/100 g gleby)	7.6 (very high)	7.6 (very high)	6.7 (medium)	5.4 (medium)
N min. (kg/ha)	43.8 (very low)	48.0 (very low)	56.8 (low)	21.4 (very low)
AP - intercropping, AK – control, N min. – mineral nitrogen				

Table 1. Soil pH and macro-element content of the soil profile (0–30 cm) in 2019 and 2023.

Weather conditions in 2021–2023

We used Selyaninov's hydrothermal coefficient (HTC) to describe the impact of weather conditions on the buckwheat and paulownia development, using the following formula:

$$K = P / (0.1 \bullet T)$$

where: K – Selyaninov's hydrothermal coefficient, P – total rainfall in the months IV-X, T – sum of daily average temperatures in specific months.[39]

The 2021 season should be considered as exceptionally dry, with 45% less rainfall in the months IV-X, compared to the multi-year period (Table 2). The low Selyaninov's hydrothermal coefficient (HTC) for the months VI-X indicate soil drought or drought. In June and September, high temperatures, well above the multi-year averages for these months, exacerbated soil water deficits. In contrast, the relatively low temperatures of April and May were responsible for the delayed resumption of paulownia's growth.

In the 2022 season, the distribution of precipitation across the months was uneven. Low Selyaninov's hydrothermal coefficients (HTC) for May and June indicate soil water deficit. There was a significant improvement in July, with rainfall exceeding the average multi-year total by 53%. The following summer months also had rainfall exceeding the average multi-year totals for the months of VIII and IX. In June and July, average monthly temperatures significantly exceeded multi-year averages by 2.3 and 1.0^{o}C, respectively. In the 2022 season, total precipitation in the IV-X period exceeded the multi-year average for that period (by 8.5%), while the average temperature did not differ from the mean.

In 2023, buckwheat emergence was prolonged due to low temperatures, while paulownia trees also resumed their growth late. Spring in the 2023 season was marked by low temperatures and low rainfall in May. The average temperatures of April and May were lower than the multi-year averages for these months by, respectively: 1.5 and 1.1^{o}C. In the following months, we recorded temperatures above the multi-year averages, with precipitation deficit in the months of May, July September and October. August was the only month when we recorded a very abundant rainfall, exceeding the multi-year average total by as much as 127%. The growing season for paulownia lasted from 163 days (in 2023) to 192 days (in 2022) (Table 3).

Table 2
Weather conditions and Sielianinov's hydrothermal coefficient in 2021–2023 by meteorological observation station (AsterMet) in Swojec near Wroclaw

Month	Temperature (°C)				Rainfall (mm)				HTC (K)		
	2021	2022	2023	*Mean* 1990–2020	2021	2022	2023	*Mean* 1990–2020	2021	2022	2023
IV	7.5	6.4	8.1	**9.6**	32.5	32.7	31.8	**32.8**	1.45	1.46	1.31
V	12.4	12.7	13.2	**14.3**	59.0	20.9	23.9	**58.9**	1.54	0.44	0.60
VI	19.8	20.1	18.7	**17.8**	38.4	39.7	73.4	**74.6**	0.65	0.58	2.09
VII	20.5	20.7	20.7	**19.7**	41.1	132.5	50.5	**86.6**	0.64	2.12	0.79
VIII	17.3	17.7	19.9	**19.2**	11.0	92.5	144.1	**63.6**	0.21	1.45	2.33
IX	15.0	14.8	17.0	**14.2**	14.5	82.0	4.7	**50.6**	0.32	2.12	0.92
X	9.5	9.1	12.0	**9.3**	10.2	8.6	30.0	**40.8**	0.35	0.25	0.81
Mean/sum (IV-X)	14.6	14.5	15.7	**14.5**	206.7	408.9	358.4	**377.0**	-	-	-

Table 2. Weather conditions and Sielianinov's hydrothermal coefficient in 2021–2023 by meteorological observation station (AsterMet) in Swojec near Wroclaw

Growing conditions/agro-technology

Prior to setting up the experiment, following the 2018 winter triticale harvest, the field was ploughed with a subsoiler plough and then the soil was kept weed-free using a cultivating unit (rotary harrow with a crushing roller). In autumn, deep pre-winter ploughing was carried out to a depth of 25 cm. In the year when the experiment started, i.e. in spring 2019, the field was ploughed once again with a subsoiler plough, and the soil was further amended using a cultivating unit. Following paulownia seedlings' planting, the soil in the inter-rows was loosened using a rotary harrow. The following year, in the spring of 2020, the soil was ploughed shallow and then fine-tilled using a cultivator. After technical pruning of the young trees in May that year, the inter-rows were tended mechanically. In 2021, after winter, we carried out shallow ploughing using a subsoiler plough, followed by a cultivating unit equipped with a string roller. By May of that year, harrowing was performed twice to control weeds. Following the buckwheat sowing, the paths were tended mechanically several times, until the crop was

harvested using combine harvester. Before winter, the soil was kept weed-free by harrowing using a rotary harrow. Tillage in 2022 included harrowing the field after winter using cultivator, followed by ploughing with a subsoiler plough to a depth of 12cm. Before buckwheat sowing, the soil was treated using a cultivating unit consisting of a rotary harrow and a crushing roller. The sowing was done using a field seeder. The paths between the plots were tended during the growth period.

Similarly, post-winter tillage in 2023 included shallow ploughing with a subsoiler plough, followed by a cultivator with a string roller before sowing buckwheat. After the buckwheat was sowed, paths between strips were being cultivates until the buckwheat was harvested using a plot combine harvester.

No mineral or organic fertilisers or pesticides were used in the experiment.

Illumination in the buckwheat field

In 2023, the period of full flowering of buckwheat (when flowers were picked to determine nectar secretion), we measured illumination at the level of plants' upper leaves in each plot, on five dates. Measurements were made under different cloud coverage conditions, between 8.30 a.m. and 12.30 p.m. In plots buckwheat and paulownia intercropping (AP), illumination was recorded in the shade of the tree crowns. All measurements were made using Czech-made PU-550 light intensity meter.

Analysis of buckwheat and paulownia biometric traits and the yield

Before harvesting the buckwheat, we randomly sampled 10 plants from each plot. The samples were sourced from the middle rows to mitigate the border effect. The biometric analysis included: plant height, number of branches, number of twigs, number of inflorescences, number of seeds and weight of full seeds per plant. The yield per plot was adjusted to 15% moisture content and converted to tonnes per hectare.

For paulownia, we measured tree height, stem girth at breast height (measured at 130 cm) and crown dimensions.

Pollinator management

Nectar secretion from buckwheat was determined using the pipette method developed by Jabłoński (2002)[40] on eight dates in 2021 (between June 28 - July 14), eleven dates in 2022 (between June 13 - July 14) and ten dates in 2023 (between June 7 - June 28). Flower samples (from at least 10 plants, from at least 10 plants protected from insect visits) were collected from the center of the canopy of each plot. The collected nectar was weighed in a laboratory and the concentrations of sugars in it were measured using an Abbe’s refractometer (KERN ABBE Refractometer ORT 1RS). The sugar mass was calculated using the formula: sugar mass = (nectar mass x % concentration of sugars)/100. The result was then converted to show value per 10 buckwheat flowers. At each date, the number of developed flowers on 10 plants was also counted and converted to account for plant density per 1 square metre and per hectare. In this way, we could calculate the availability of raw sugar for bees per 1 ha/day of measurement. For each day of observation, we also determined the number of bees visiting the plot (block) between 7.30 a.m. and 8.00 a.m.

Statistical analysis

To assess the impact of the cultivation method across different years of study on the biometric traits and yield of buckwheat, we performed a two-factor ANOVA analysis using Statistica 13.1 software. In case of significant differences between means, we compared them using the HSD-Tukey test, with a significance level of $\alpha = 0.05$. We included mean results, maximum, minimum values as well as standard deviations. To assess nectar secretion across groups characterised by the variant, we performed a one-way analysis of variance (ANOVA) preceded by a Shapiro-Wilk test for normality. All analyses were conducted at the 5% significance level using the STATISTICA (data analysis software system) package, v. 13.1 by StatSoft, Inc. (2014).[41] To assess the differences between the mean values of the following parameters: mass nectar of 10 flowers of buckwheat (mg), mass sugars of 10 flowers of buckwheat (mg), average number of flowers per 1 plant per 1 day of buckwheat, average number of flowers (million/1 ha^{-1} per day of observation, availability of raw sugar (kg per 1 ha), average number of bees for 1 block (pcs) between groups (AP) and (AK) we applied Student's independent samples *t* test. We performed separate analyses for each year in the 2021–2023 period and a joint analysis for all samples collected over three years.

Experimental research and field studies on plants (either cultivated or wild), including the collection of plant material are complying with relevant institutional, national, and international guidelines and legislation. I declare that the plant material used for our study was purchased from Oxytree Solution Poland. We did not use endangered plant species for the experiments.

RESULTS

Buckwheat and paulownia development phases

The start of vegetation phase of both intercropped species occurred in early May, regardless of the year. Buckwheat emergence in the 2022 season was half as long as in the previous year, while in 2023 extended over as many as 18 days (Table 3), when it was prolonged due to low temperatures. Vegetation phase for paulownia trees also resumed late in 2023. Buckwheat developed flower buds at between 30 days (2022) to 41 days (2023) following sowing. Full flowering lasted from 18 days (2022) to 33 days (2021). The shortened flowering period, especially in 2022, was due to high air temperatures in the months VI - VII and the absence of rainfall during this time. During the 2023 season, full flowering lasted 29 days. Buckwheat was harvested after the following periods: 85 days (2021), 69 days (2022) and 117 days (2023) after sowing.

Table 3
Oxytree and buckwheat phenological phases in 2021–2023

Date	Paulownia	Number of days since resumption of growth	Buckwheat	Number of days since sowing
	phase		phase	
2021				
11.05.2021	resumption of vegetation	-	sowing	
26.05.2021	development of leaf buds	15	open cotyledons	15
14.06.2021	shoot (crown) growth	34	flower buds	34
23.06.2021	crown growth	43	beginning of flowering	43
29.06.2021	crown growth	49	full bloom	49
17.07.2021	crown growth	67	brown seeds	67
04.08.2021	crown growth	85	harvest	85
18.09.2021	first leaves turn yellow	130	–	–
21.11.2021	leaves fall (end of vegetation phase)	192	–	–
2022				
04.05.2022	resumption of vegetation	-	sowing	-
11.05.2022	development of leaf buds	7	open cotyledons	7
10.06.2022	crown growth	30	flower buds	30
17.06.2022	crown growth	36	beginning of flowering	36
21.06.2022	crown growth	40	full bloom	40
29.06.2022	crown growth	48	brown seeds	48
20.07.2022	crown growth	69	harvest	69
28.10.2022	leaves turning yellow	167	–	–
09.11.2022	leaves fall (end of vegetation phase)	179	–	–
2023				
20.04.2023	-	-	sowing	-
08.05.2023	resumption of vegetation	-	open cotyledons	18

Date	Paulownia	Number of days since resumption of growth	Buckwheat	Number of days since sowing
	phase		phase	
10.05.2023	development of leaf buds	2	first leaves	20
31.05.2023	crown growth	23	flower buds	41
12.06.2023	crown development	35	full bloom	53
26.06.2023	crown growth	49	brown seeds	60
22.08.2023	crown growth	106	harvest	117
29.09.2023	leaves turning yellow	138	-	-
24.11	leaves fall (end of vegetation)	163	-	-

Table 3 Oxytree and buckwheat phenological phases in 2021–2023

Effect of intercropping on biometric traits, flowering biology and yield of buckwheat

The cultivation system had no significant impact on the variation in the morphological traits of buckwheat, except the number of branches on the main shoot and the total number of branches (Table 4), which may have been due to an increased sun exposition in the control variant, where buckwheat branched more strongly. These traits were mainly modified in line with the weather pattern in the specific years of the study. The total number of set seeds was significantly lower in the 2021 season when compared to other seasons. The tallest plants, which were also least branching, occurred in the 2023 season.

Table 4
Selected morphological and flowering-related traits of buckwheat (averages for combination and individual years)

Specification	Plant height	Number of branches on the main shoot	Total number of branches	Number of inflorescences per plant	Total number of seeds
AP (intercropping)	49.2	0.98	2.51	5.39	26.4
AK (control)	49.6	1.36	3.04	6.13	26,4
$NIR_{0.05}$ $LSD_{0.05}$	**ns**	**0.37**	**0.43**	**ns**	**ns**
2021	47.3	1.41	2.36	6.84	15.5
2022	47.1	1.38	4.22	5.55	28.8
2023	53.9	0.72	1.74	4.89	34.9
$NIR_{0.05}$ $LSD_{0.05}$	**5.27**	**0.45**	**0.53**	**1.33**	**8.5**

Table 4. Selected morphological and flowering-related traits of buckwheat (averages for combination and individual years)

The cultivation method variant did not cause differentiation in either the structure elements or the yield itself (Table 5). There were significant differences in yield in individual years of the study, with the lowest seed yield recorded in 2021 due to the least favourable weather conditions and the highest in 2023. Significantly higher yield of buckwheat in the 2023 season was influenced by the significantly higher number of whole seeds and seed weight per plant. Yields ranged from 0.39 (2021) to 1.59 (2023) tonnes per hectare.

Table 5
Seed yield and its structure (average for combinations and years)

Specification	Number of full seeds items	Weight of seeds per plant g	Seed yield t/ha
AP (intercropping)	16.1	0.36	0.91
AK (control)	14.9	0.37	0.93
$NIR_{0.05}$ $LSD_{0.05}$	**ns**	**ns**	**ns**
2021	6.42	0.16	0.39
2022	14.3	0.31	0.77
2023	25.7	0.64	1.59
$NIR_{0.05}$ $LSD_{0.05}$	**5.10**	**0.17**	**0.42**

Table 5. Seed yield and its structure (average for combinations and years)

Selected trunk and crown parameters of paulownia in 2021–2023

The average height of the trees at the beginning of the growing season 2021 was 160.5 cm, at the end of the 2022 season 311 cm, and in 2023 – 507 cm. Tree crown sizes measured in October 2022 were on average: 156 (height) x 209cm (width), while in 2023, 308 (height) x 357cm (width). Trunk girths at breast height (measured at 130cm) at the end of the 2021, 2022 and 2023 seasons were respectively: 16.4cm, 17.9cm, 22.7cm. No flowering of paulownia was recorded during the years covered by the study.

Effect of intercropping on illumination during the 2023 season

Illumination varied between the sites under study (Table 6). It was found to be higher in the buckwheat monoculture crop, suggesting that paulownia may reduce light for buckwheat. At the same time, a lower solar exposure may have reduced the effects of soil drought stress, as the trees have contributed to increased water retention. It should be noted that during the early period of buckwheat development (emergence and foliage), paulownia and buckwheat are, to a degree, in competition for light.

Table 6
Illumination during buckwheat bloom in lux (lx)

Data	Measurement		Comments
	AP	AK	
05.06.2023	19.2	75.3	cloudless, sunny, warm, buckwheat budding, 10.00 a.m.
$NIR_{0,05}$ $LSD_{0·05}$	16.0		
07.06.2023	31.3	91.1	Clouds/sunshine, "subdued" sky, dry, warm, first flowers, 12.30 p.m.
$NIR_{0,05}$ $LSD_{0.05}$	21,6		
12.06.2023	9.3	58.5	sunny, dry, warm, full bloom, 9.00 a.m.
$NIR_{0.05}LSD_{0.05}$	10,2		
14.06.2023	19.4	28.1	cloudy, full flowering, before storm, 11.00 a.m.
$NIR_{0.05}LSD_{0.05}$	3.4		
26.06.2023	12.1	57.8	Sunny, very warm, first brown seeds, 8.30 a.m.
$NIR_{0.05}$ $LSD_{0.05}$	20.3		

Table 6. Illumination during buckwheat bloom in lux (lx)

Effect of intercropping on the beekeeping value of buckwheat

The results show clear influence of weather on the relevant parameters. The mass of nectar and sugars per 10 buckwheat flowers reached the highest values in 2023 for both groups. The lowest values for these parameters were not as consistent, with 2022 for the AP group and 2021 for the AK group. The established availability of raw sugar for pollinators demonstrated that 2022 was the least favourable year, with the lowest values for both groups. It was interesting to note that in 2023 buckwheat had the lowest number of flowers per plant and per unit area, but due to the high sugar content in nectar and nectar mass, the AK group achieved the highest result. The AP group had a lower availability of raw sugar in this period, but the difference was not statistically significant. (Table 7). Assessing the averages for the three-year period, we found that the mass of sugars per 10 buckwheat flowers in the AK group was slightly higher (0.55 mg) than in the AP group. We found a similar relationship when assessing the nectar mass per 10 flowers, with higher values in the control group. During the study period, buckwheat in the AP group showed higher number of developed flowers than in the control group, which was reflected in the number of flowers per hectare per observation day. However, when converted into raw sugar availability, the increased number of flowers in the AP group did not push the value in this parameter beyond that in the AK control group (1.95 kg and 2.12 kg, respectively). For both groups, there was also no change in the attractiveness of the crop to bees, and the values obtained were not markedly different (Table 7). The statistical analysis did not show significance of differences between the two groups in the three-year period for the buckwheat parameters presented below. The observed differences between years are mainly due to the impact of weather during the buckwheat growing season. 2023 proved to be the most favourable year, while 2022 was the least favourable. As we found no significant differences between the control group and the group assessed at the 5% level, we did not proceed with further statistical analyses.

When assessing the number of bees visiting the buckwheat plots, we noted no differences in the three study years, but in 2021 there was a statistically significant increase in bee visits in the AK group compared to the AP group *(p = 0,036).*

Table 7
Beekeeping value of buckwheat in intercropping

Specification	Parameter	2021		2022		2023		Years 2021–2023	
		AP	AK	AP	AK	AP	AK	AP	AK
Mass of sugars of 10 flowers of buckwheat (mg)	$\bar{x}$	**0.46**	**0.42**	**0.38**	**0.46**	**0.64**	**0.75**	**0.49**	**0.55**
	SD	0.09	0.12	0.12	0.11	0.21	0.27	0.18	0.23
	P value	0.710		0.377		0.069		0.208	
Mass of nectar of 10 flowers of buckwheat (mg)	$\bar{x}$	**4.18**	**3.78**	**3.79**	**4.92**	**6.10**	**7.83**	**4.69**	**5.61**
	SD	1.99	2.24	2.81	3.03	2.03	2.00	2.49	2.96
	P value	0.439		0.126		0.345		0.334	
Average number of flowers on 1 plant per 1 day of observation	$\bar{x}$	**18.56**	**21.08**	**18.14**	**14.47**	**12.99**	**13.38**	**16.48**	**15.92**
	SD	3.37	6.11	6.75	4.72	4.45	3.14	5.67	5.58
	P value	0.410		0.155		0.822		0.713	
The average number of flowers million/1 ha^{-1} per day of observation	$\bar{x}$	**46.40**	**52.70**	**45.35**	**36.18**	**32.48**	**33.45**	**41.20**	**39.80**
	SD	8.44	15.28	16.87	11.79	11.11	7.85	14.17	13.96
	P value	0.325		0.155		0.822		0.705	
Availability of raw sugar in kg per 1 ha	$\bar{x}$	**2.14**	**2.25**	**1.72**	**1.65**	**2.05**	**2.53**	**1.95**	**2.12**
	SD	0.62	1.19	0.73	0.64	0.92	1.20	0.77	1.05
	P value	0.825		0.677		0.322		0.566	
Average number of bees for 1 block (pcs.)	$\bar{x}$	**20.93**	**30.30**	**10.89**	**8.85**	**37.80**	**32.10**	**22.94**	**22.79**
	SD	7.64	8.46	12.93	11.50	40.73	38.61	27.29	25.84
	P value	**0.036**		0.700		0.752		0.983	

Table 7 Beekeeping value of buckwheat in intercropping

DISCUSSION

Intercropping is a system in which two or more crop species are sown or planted simultaneously in the same field and during the same growing season.[42, 43] The benefits of such cultivation include reduction of the impact of biotic and abiotic environmental stresses on yield - above all, the protection of the soil against erosion and excessive evaporation of water from the soil. When planning intercropping of several plant species, one should

consider possible adverse effects of allelopathic plant activity, light distribution between crops, root system structure, development and growth rate, while maintaining botanical distinctiveness.[44–46]

The primary factor determining high yield is light. Several studies have found that competition for light is greater than competition for soil resources in temperate and humid climate regions, where crops grown in such a system are usually fertilised and rainfall is relatively abundant, providing an adequate supply of water.[45,47] Bouttier et al. (2014)[44] demonstrated that he availability of light for intercropping near hybrid poplar was lowest due to tree size and planting density per row. Reduction in crop yield, high ratio of root density per unit of intercrop biomass, and high values of hybrid poplar (*Populus deltoides, Populus nigra*) root densities per area, as well as low soil nitrogen concentration all suggest depletion of soil resources. Impact of poplar in the study by Alama et al. (2014)[48] on agricultural crop yield was greater than for red oak. In the study by Bouttier et al. (2014)[44] the yield of plants (*Phleum pratens* L. and *Trifolium pratense* L.) decreased near trees, especially near hybrid poplars. This was mainly due to competition for light, and to a lesser extent to root competition for resources, even if soil resources and fertilisation levels were low. In our study, there was no significant effect of intercropping on buckwheat yield, either in terms of competition for light or for soil resources.

In intercropping involving well-matched species, interspecies competition proves stimulating for both cultivated species or at least one of them, which manifests in an increase in yield quantity and quality. Changes in soil properties in an orchard where intercropping was used had a positive effect on walnut productivity. Walnut is a deciduous species with late developing leaves, so shading by its crown, which coincides with later stages of barley development, may not have a critical limiting effect on barley yield. In addition, barley is a C3 crop, which means it is less susceptible to negative impact of shading, as only 50% of full sunlight is sufficient for the plant to become fully light-saturated.[49] Intercropping with winter barley was 53% more productive per unit area and 83% more water-intensive than growing walnut and barley separately, but also 48% more productive per unit area and 70% more water-intensive than the walnut-barley system.[46]

Yield advantage in intercropping is measured by the so-called competition functions, such as relative yield total (RYT), relative value total (RVT) or the yield equivalent to the base-level yield. In an experiment by Mandal et al. (2014)[49] recorded 5,48 t ha^{-1} of maize equivalent yield (MEY) in maize and soya intercropping (1:2) against 2,48 t ha^{-1} for just maize. The relative yield total (RYT) of the intercropping was higher than in monoculture in the different experiments, indicating a yield advantage.[50] Manasa et al.[51] mentioned that MEY was 7,6 t ha^{-1}, when maize was intercropped with groundnut (2:2), compared to a maize yield in monoculture, which was 5,7 t ha^{-1}, while RYT amounted to 1,47. In our study, the average yield of buckwheat in monoculture was 0,93 t ha^{-1} and in intercropping was 0,91 t ha^{-1} and the difference was not statistically significant.

The value of crop yield in intercropping is linked to the compensation principle. The probability of yield reduction due to a disease, pests or extreme weather conditions is significantly lower in intercropping. It has been shown that at any level of stress factor, intercropping has a significantly lower probability of failure than monoculture.[52] In intercropping, one species can change the microclimate for the other species, which can keep the emergence of pests and diseases in check, resulting in greater productivity and stability.[53] Intercropping tends to be more popular in developing countries, perhaps because it is assumed that it gives more stable yields than monocultures.[54] Many field experiments have looked into yield stability in intercropping and the results are

sometimes inconclusive.[55– 57] Li et al. (2020)[58] noted that an absolute yield increase in intercropping, compared to monoculture was greatest for maize intercropped with short-grain cereals or legumes.

Alekseyeva and Bureyk (2000)[32] demonstrated that nectar productivity depends on the flowering stage. They also argued that there is a strong correlation between nectar abundance and seed yield. Płażek at al. (2023)[59] only established that there was a correlation between nectar and seed mass, while any of the sugar contents had no impact on the seed yield. A characteristic feature of common buckwheat is the low percentage of seeds set in relation to the produced inflorescences. According to Jacquemart et al. (2012)[60] and Farooq et al. (2008)[61] this is due to internal defects, i.e. male or female sterility or abnormalities of the embryo. According to (Słomka et al. 2017)[62] and Płażek et al. 2022)[63] there was a very high pollen viability (99%) and germination of all Polish buckwheat varieties tested, so the main reason for the lack of fertilisation was a high percentage of degenerated embryo sacs.

Moreover, Lee and Heimpel (2003)[64] demonstrated that buckwheat secreted more quantities of nectar in early morning. In the study by Płążek et al. (2023)[59] there was no considerable difference in hexose content assessed during two flowering stages, but some differences were noted between the genotypes. The volume and mass of buckwheat nectar depend on the genotype, the time of day (illumination) and the position of the flower on the plant.[31, 32, 61] Nectar secreted in the early flowering phase is characterised by greater mass and volume in most buckwheat genotypes. In our study, more nectar was found in the buckwheat crop monoculture. It contained more individual sugars than in the full flowering phase. Buckwheat flowers for a long time during its vegetation period, enabling various insects to frequently visit its inflorescences. Płażek et al. (2023)[59] showed a positive correlation between total sugars and amino acids in nectar and seed yield in buckwheat varieties. Cawoy et al (2008; 2009)[31,65] also led positive correlation between the amount of nectar secretion of buckwheat flowers and the frequency of visits by pollinators. The increase in the level of nectar secretion by the plant attracts a greater number of bees and other insects, increasing the number of visits to the flowers, thus improving the possibility of their cross-pollination. Despite the fact that plants may have a very high number of flowers, only 5–10% of them form seeds,[66,67] which is mostly due to the allogamy of buckwheat. [60,61] Buckwheat flowers develop early in the morning and bloom only for one day. To pollinate a single flower, at least 10 grains of foreign pollen are necessary, and the time required for this process is less one hour.[68] In Poland, Germany, Korea, and the US, the main buckwheat pollinators are *Apidae* (honeybee and bumblebee). A worker bee (*Apis mellifera*) visits an average 14–20 flowers/min and works buckwheat for 4–5 h/day, effectively transferring pollen between the plants. Other bees, syrphidae, and diptera can also make a significant contribution to buckwheat pollination, especially in Asia.[60,69]

The decline in numbers of pollinating insects in agricultural areas has been observed for several decades, partly due to the simplification of the landscape within intensive agro-ecosystems.[66] Intensive agriculture is one of the main causes of recent insect number declines. Such loss of biodiversity has created the need to develop integrated farming methods combining high yields with biodiversity conservation. Intercropping has been shown to lead to a significant increase in bumblebee and honeybee activity, as well as in bee species diversity. [22]

On farms with perennial cropping systems such as orchards, vineyards or energy crop plantations, long-term ground cover may also be a desirable outcome.

As a fast-growing crop, buckwheat is commonly used for weed control in perennial crops. Its long flowering period can also benefit wild pollinators.[70] Our results confirm suitability of buckwheat for these purposes. We have demonstrated that intercropping does not reduce buckwheat value as an agricultural or nectar crop. Also, cultivation of perennial nectar-producing wild plant species (WPS) for biogas helps to improve ecosystem services such as habitat provision (plant pollination), erosion mitigation, groundwater protection through increased retention, and carbon sequestration.[71]

Pollination as an ecosystem service can significantly increase production of more than 70% of agricultural crops grown around the world.[72,73] Pollination of both wild and agricultural plants is carried out by bees and other pollinating insects.[74] Bees are significant in terms of pollination due to their need to feed on pollen and nectar and their use of plants as breeding sites.[75] Pollination is essential for the functioning of the ecosystem since it contributes to the maintenance and growth of plant diversity.

Declines in pollinator populations can affect plant pollination, which can have a direct impact on crop production, food security and human well-being.[76]

Along with increasing economic and environmental costs associated with fertiliser use, there has been a growing demand for low-input agroecological solutions, such as agroforestry systems. However, little is known about the effect of shading on crop performance. Researched tried to determine whether intercropping legumes, soybean (*Glycine max L. Merr.*) and alfalfa (*Medicago sativa*) with wheat (*Triticum turgidum durum*) is beneficial for productivity, particularly under shaded conditions associated with tree-based intercropping. Legume-based intercropping can increase nutrient supply and growth, but these beneficial effects will depend on matching species selection to light levels within the tree-based intercropping sites.[77]

AFS constitute an alternative solution for improving environmental conditions in agroecosystems. The suggestion to diversify the area promotes species diversity, increased vegetation layers, increased vegetation shading, reduced harmful effects of high temperatures and improved microclimatic conditions of both the environment and the soil. It our case it was clear that increased shading favoured increased bee abundance in the area. For that reason such solution would be preferable, also for of long-term climate change mitigation by AFS, as relevant changes also severely affected the behaviour of pollinating bees.[78]

Conclusions

Intercropping buckwheat with paulownia can provide a food source for some insect species on arable land. While the contribution of intercropping per unit area to insect conservation may be small, its potential support for biodiversity could be enormous. Buckwheat has a high beekeeping value and intercropping with paulownia results in an increase in the average number of flowers per plant per day of observation and the average number of flowers in millions per hectare per day of observation. Millions of flowers are present during the buckwheat flowering, maintaining high density of wild pollinators due to considerable nectar resources. Results from three growing seasons indicate that intercropping buckwheat together with Oxytree did not result in a decrease in the values of parameters relevant to the beekeeping value of buckwheat in terms of its attractiveness to pollinators. Nor did the intercropping of buckwheat between rows of Paulownia trees result in a deterioration of the biometric and yield characteristics of this annual crop. There are currently no data available to compare the results of our study with other studies of growing buckwheat in an agroforest system. However, the

intercropping of buckwheat together with paulownia has proven to enable efficient use of the area between the rows of Oxytree without deteriorating the conditions for both nectarisation and yield of this crop.

Declarations

Competing interests

The authors declare no competing interests.

Funding

The APC/BPC is financed/co-financed by Wroclaw University of Environmental and Life Sciences.

Author Contribution

P.CH., M.L. and A.J.R. —wrote the main manucript, P.CH. entomological analysis, P.B.—literature, visualisation P.CH. , M.L. - statistical analysis.

Data Availability

All data generated or analysed during this study are included in this published article.

References

1. Foley, Jonathan A. *et al.* Global Consequences of Land Use *Sci.***309**, 570-574 https:/doi.org/10.1126/science.1111772 (2005).
2. Wagner, D.L. Insect decline in the Anthropocese. *Ann. Rev. Entomol*. **65**, 457–480 (2020).
3. Wagner, D.L., Grames, E.M., Forister, M.L. *et al.* Insect decline in the Anthropocene: Death by a thousand cuts. *Proc. Natl. Acad. Sci*. USA **118**, e2023989118 (2021).
4. Lin B.B. Resilience in Agriculture through Crop Diversification: Adaptive Management for Environmental Change, *BioScience*, **61**, 3, 183–193 https://doi.org/10.1525/bio.2011.61.3.4 (2011).
5. Brandmeier *et al*.Intercropping in high input agriculture supports arthropod diversity without risking significant yield losses*Basic Appl. Ecol*. **53**, 26-38 https://doi.org/10.1016/j.baae.2021.02.011 (2021).
6. Hüber C.,Zettl F., Hartung J., Lindenlauf Muller M. The impact of maize-bean intercropping on insect biodiversity, *Basic Appl. Ecology* **61**, 1-9 (2022).
7. Krupinsky, J.M., Bailey, K.L., McMullen, M.P. Gossen, B. D., Turkington, T. K. Managing plant disease risk in diversified cropping systems. *Agronom. J*. **94**, 198–209. 2002
8. Hufnagel J., Reckling M.& Ewert F. Diverse approaches to crop diversification in agricultural research. A review, *Agronom. for Sustain. Develop*. **40**, 14 https://doi.org/10.1007/s13593-020-00617-4 (2020).

9. Tscharntke *et al.* Global food security, biodiversity conservation and the future of agricultural intensification. *Biol Conserv***151**(1), 53–59. https://doi.org/10.1016/j.biocon.2012.01.068(2012)
10. Borek R, Agroforestry Systems in Poland a preliminary identification. Papers on global change IGBP, 22, 37–51 https://doi.org/10.1515/igbp-2015-0014 (2015).
11. Poradnik Agroleśnictwo (2022) Available at https://www.iung.pl/2022/08/25/poradnik-agrolesnictwo-systemy-rolno-lesne/
12. Potts, S.G. *et al.* Vanbergen Safeguarding pollinators and their values to human well-being *Nature*, **540** (7632)220-229 https://doi.org/10.1038/nature20588 (2016).
13. Rhodes (2018)
14. Norris, S.L. *et al.* Intercropping flowering plants in maize systems increases pollinator diversity *Agric. Forest Entomol*., **20** (2) 246-254, 10.1111/afe.12251(2018).
15. Redwitz, C.,Glemnitz, M., Hoffmann, J., Brose, R., Verch, G., Barkusky, D,. Bellingrath-Kimura Microsegregation in maize cropping—a chance to improve farmland biodiversity *Gesunde Pflanzen*, **71** (2), 87-102, https://doi.org/10.1007/s10343-019-00457-7(2019).
16. Chorbiński P., Kozak M., Liszewski M., Migdał P. Stan i perspektywy rozwoju pszczelarstwa na Dolnym Ślasku / red. nauk.: Paweł Chorbiński ; Wrocław : AD FONTES Agencja Wydawnicza, 159 s. (2019).
17. Liszewski M., Chorbiński P. Intercropping of buckwheat (*Fagopyrum esculentum* L.) with oxytree (*Paulownia elongata x P. fortunei*) in Polish conditions. EURAF (2022).
18. Klein, A.M., Vaissiere, B.E., Cane, J.H., Steffan-Dewenter I., Cunningham, S.A., Kremen, C.*et al.* Importance of pollinators in changing landscapes for world crops, Proceed. Biolog. Sci., **274**, 303-313https://doi.org/10.1098/rspb.2006.3721 (2007).
19. Sikora V. Buckwheat as a honey plant. Presented in part at *Proceedings of the XXXI advising beekeepers*, *Union of Beekeeping Organizations of Vojvodina, Novi Sad, Serbia, March 2013*, pp. 45–60, ISBN 978-86-89519-00-6. (in Serbian) (2013).
20. Kortesniemi, M., Rosenvald, S., Laaksonena, O., Vanaga, A., Ollikkac, T., Vene, K., Yanga, B. Sensory and chemical profiles of Finnish honeys of different botanical origins and consumer preferences. *Food Chem.***246**, 351–359. https://doi.org/10.1016/j.foodchem.2017.10.069 (2018).
21. Pasini, F, Gardini, S, Marcazzan, G.L, Caboni, M.F. Buckwheat honeys: screening of composition and properties. *Food Chem.***141**, 2802–2811 https://doi.org/10.1016/j.food-chem.2013.05.102 **(**2013).
22. Borutinskaite V, Treigyte G, Čeksteryte V, Kurtinaitiene B, Navakauskiene R. Proteomic identification and enzymatic activity of buckwheat (*Fagopyrum esculentum*) honey based on different assays. *J. Food Nutr. Res.***57**, 57–69 (2018).
23. Marshall, H. G. and Y. Pomeranz. Buckwheat: Description, breeding, production and, utilization. Pp. 157-210 in Advances in Cereal Science and Technology. 5. (Y. Pomeranz, ed.). American Association of Cereal Chemists Incorporated, St. Paul, Minnesot (1982).
24. Racys, J., Montviliene R. Effect of bees-pollinators in buckwheat [Fagopyrum esculentum Moench] crops *J. Apicultural Sci.***49,** 1, (2005).
25. Campbell C.G., 1997. Buckwheat: Fagopyrum esculentum Moench. Promoting the conservation and use of underutilized and neglected crops. 19. Institute of Plant Genetics and Crop Plant Research, Gatersleben/International Plant Genetic Resources Institute, Rome, Italy, 25.

26. Quinet, M., Cawoy, V., Lefèvre, I, Van Miegroet, F., Jacquemart, A-L., Kinet, J.M. Inflorescence structure and control of flowering time and duration by light in buckwheat (*Fagopyrum esculentum* Moench). *J. Experimental Botan*. **55**, 1509-1517(2004).
27. Grigorenko V. Okratnosti posešèenija pèelami greèichi. *Pèelovodstvo***10**, 18-19. (1979)
28. Björkman, T. Guide to buckwheat production in the Northeast. N.Y. State Agr. and Ext. Service, Cornell Univ. Geneva, NY. (Online at: http://www.nysaes.cornell.edu/hort/faculty/bjorkman/buck/guide/index.html) (2002).
29. Baker, H.G. Floral nectar sugar constituents in relation to pollinator type. In *Handbook of Experimental Pollination Biology*; Jones, C.E., Little, R.J., Eds.; Van Nostrand Reynold Comp.: New York, NY, USA, pp. 117–141(1983).
30. Jabłoński B. 2003. Metodyka badań obfitości nektarowania kwiatów i oceny miododajności roślin. Wyd. ISK, Skierniewice: ss. 30.
31. Cawoy, V., Kinet, J. M. & Jacquemart, A. L. Morphology of nectaries and biology of nectar production in the distylous species Fagopyrum esculentum. *Ann. Bot*. **1025**, 675–684. https:/ https://doi.org/10.1093/aob/mcn150 (2008).
32. Alekseyeva, E. S. & Bureyko, A. L. Bee visitation, nectar productivity and pollen efciency of common buckwheat. *Fagopyrum* **17**, 77–80 (2000).
33. Farooq, S. *et al.* Cultivation, agronomic practices, and growth performance of buckwheat. In Molecular Breeding and Nutritional Aspects of Buckwheat (eds Zhou, M. et al.) 299–319 (Academic Press, 2016). https://doi.org/10.1016/B978-0-12-803692-1.00023-7 (2016).
34. Taylor, D. B. & Obendorf, R. L. Quantitative assessment of some factors limiting seed set in buckwheat. *Crop Sci*. **41**/6, 1792–1799 https://doi.org/10.2135/cropsci2001.1792 (2001)
35. Halbrecq, B., Romedenne, P. & Ledent, J. F. Evolution of flowering, ripening and seed set in buckwheat (Fagopyrum esculentum Moench): Quantitative analysis. *Eur. J. Agron*. **23**, 209–224. https://doi.org/10.1016/j.eja.2004.11.006 (2005).
36. Zhu, Z.H., Chao, C.J., Lu, X.Y.&Xiong, Y.G. Paulownia in China: Cultivation and Utilization. Asian Network for Biological Sciences, Republic of Singapore and International Development Research Centre, Canada (1986).
37. Oxytree 2024 dostępne pod linkiem: https://oxytree.pl/kwitnace-oxytree/
38. IUSS Working Group WRB. 2022. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria.
39. Radomski Cz., 1987. Agrometeorologia. PWN, Warszawa
40. Jabłoński B. Notes on the method to investigate the nectar secretion rate in flowers. *J. Apicultural Sci.*, 46(2), 117-125. (2002).
41. Statistica. Data Analysis Software System, Version 12 (Statsoft Inc., 2014)
42. Li, C., Hoffland, E., Kuyper, T.W. *et al.* Syndromes of production in intercropping impact yield gains. *Nat. Plants***6**, 653–660 https://doi.org/10.1038/s41477-020-0680-9 (2020).
43. Bedoussac, L., Journet, EP., Hauggaard-Nielsen, H. *et al.* Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. *Agron. Sustain. Dev.***35**, 911–935 https://doi.org/10.1007/s13593-014-0277-7(2015).

44. Bouttier L. *et al.* Vertical root separation and light interception in a temperate tree-based intercropping system of Eastern Canada, *Agroforest Syst* **88**, 693–706 https://doi.org/10.1007/s10457-014-9721-6 (2014).
45. Ding, S. & Su P. Effects of tree shading on maize crop within a poplar-maize compound system in Hexi Corridor oasis, northwestern China, Agroforestry System, **80**, 117-129/doi.org/10.1093/aob/mcn150 (2010).
46. Žalac, H., Zebec, V., Ivezi´c, V., Herman, G. Land and Water Productivity in Intercropped Systems of Walnut—Buckwheat and Walnut–Barley: A Case Study. *Sustain.*, **14**, 6096. https:// doi.org/10.3390/su1410609 (2022).
47. Friday, J.B, Fownes, J.H. Competition for light between hedgerows and maize in an alley cropping system in Hawaii, USA. *Agroforestry Sys.***55**, 125–137(2002).
48. Alam M, Olivier A, Paquette A, Dupras J, Revéret J-P, Messier C A general framework for the quantification and valuation of ecosystem services of tree-based intercropping systems. Agroforestry Systems accepted AGFO-D-13-00239 (2014).
49. Mandal, M.K., Banerjee, M., Banerjee, H., Alipatra, A., Malik, G.C. Productivity of maize (Zea mays) based intercropping system during kharif season under red and lateritic tract of West Bengal. Bioscan 9, 31–35 (2014).
50. Baghdadi, A., Halim, R.A., Othman, R., Yusof, M.M., Atashgahi, A.R.M. Productivity, relative yield and plant growth of forage corn intercropped with soybean under different crop combination ratio. *Legume Res.* **39,** 558–564 (2016).
51. Manasa, P., Maitra, S.&Barman, S. Yield Attributes, yield, competitive ability and economics of summer maize-legume intercropping system. *Int. J. Agric. Environ. Biotechnol.***13,** 3–38.(2020).
52. Rao, M.R and Willey, R.W. Competitive Ratio for Quantifying Competition between Intercrops. *Experimental Agric.*, **16,** 117-125. http://dx.doi.org/10.1017/S0014479700010802 (1980).
53. Md. Raseduzzaman, Erik Steen Jensen, Does intercropping enhance yield stability in arable crop production? A meta-analysis, *Eur. J. Agronom.*, **91**, 25-33 https://doi.org/10.1016/j.eja.2017.09.009 (2017).
54. Sileshi Gudeta W., Legesse Kassa Debusho, and Festus K. Akinnifesi Can Integration of Legume Trees Increase Yield Stability in Rainfed Maize Cropping Systems in Southern Africa?
55. Płażek, A. *et al.* Effects of high temperature on embryological development and hormone profile in flowers and leaves of common buckwheat (Fagopyrum esculentum Moench). *Int. J. Mol. Sci.***20/**7, 1705. https://doi.org/10.3390/ijms20071705 (2019).
56. Luo S., Yu L., Liu Y., Zhang Y., Yang W., Li Z., et al. (2016). Effects of reduced nitrogen input on productivity and N2O emissions in a sugarcane/soybean intercropping system. Eur. J. Agron. 81 78–85. 10.1016/j.eja.2016.09.002
57. Dapaah, H. K., Asafu-Agyei, J. N., Ennin, S. A., and Yamoah, C. (2003). Yield stability of cassava, maize, soya bean and cowpea intercrops. Journal of Agricultural Science, 140, 73-82. https://doi.org/10.1017/S0021859602002770
58. Li, C., Hoffland, E., Kuyper, T.W. et al. Syndromes of production in intercropping impact yield gains. Nat. Plants 6, 653–660 (2020). https://doi.org/10.1038/s41477-020-0680-9
59. Płażek, A., Dziurka, M., Słomka, A. & Kopeć, P. Te efect of stimulants on nectar composition, fowering, and seed yield of common buckwheat (*Fagopyrum esculentum* Moench). *Int. J. Mol. Sci.***24**, 12852.

https://doi.org/10.3390/ijms241612852 (2023).

60. Jacquemart, A., Cawoy, V., Kinet, J.M., Ledent, J.F., Quinet, M. Is buckwheat (*Fagopyrum esculentum* Moench) still a valuable crop today? *Eur. J. Plant Sci. Biotechnol.* **6,** 1–10(**2012).**
61. Farooq (2008)
62. Słomka, A. *et al.* Embryological background of low seed set in distylous common buckwheat (Fagopyrum esculentum Moench) with biased morph ratios, and biostimulant-induced improvement of it. *Crop Pasture Sci.* **68**, 680–690. https://doi.org/10.1071/ CP17009 (2017).
63. Płażek A. *et al.*, Study of the possibility of increasing the vitality and pollination of buckwheat flowers in order to obtain a higher seed yield. Biul. IHAR, **295**, 271–276, E-ISSN: 2657–8913 (2021)
64. Lee, J. & Heimpel, G. E. Nectar availability and parasitoid sugar feeding. In: Van Drische, R. G. (Ed) Proceedings of the 1th International Symposium the Biological Control of Arthropods, 220–225 (2003).
65. Cawoy V. et al. Floral Biology of Common Buckwheat (Fagopyrum esculentum Moench), *Europ. J. Plant Sci. Biotech.* (2009).
66. Liszewski M.. Gryka – roślina niedoceniana. Sem. Nauk., Wyd. WTN Wrocław **8**(59), 155–161 (2009).
67. Ścigalska B., Biologiczne i siedliskowe uwarunkowania uprawy gryki w Polsce. Post. Nauk. Rol. **1**, 93–109 (2004).
68. BjÖRkman T., Role of Honey Bees (Hymenoptera: Apidae) in the Pollination of Buckwheat in Eastern North America, *J. Economic Entomolg.* **88**, 6, 1, 1739–1745, https://doi.org/10.1093/jee/88.6.1739(1995).
69. Aryal, S., Ghost S., Jung H., Ecosystem Services of Honey Bees; Regulating, Provisioning and Cultural Functions, *J. Apicultural*, **35**(2), 119-128 https://doi.org/10.17519/apiculture.2020.06.35.2.119 (2020).
70. Opportunities in Agriculture, available at https://www.sare.org/wp-content/uploads/Cover-Cropping-for-Pollinators-and-Beneficial-Insects.pdf, accessed 15.02.2024
71. Amy, C.et al. F. Flower Strips in Wheat Intercropping System: Effect on Pollinator Abundance and Diversity in Belgium. Insects, 9, 114. https://doi.org/10.3390/insects9030114 (2018)
72. Cossel, M., Heinzel, K., Patiño Lordello G., Aron Winkler A., Lauria M.V., Gandamalla, G., Jablonowski, N.D. Exploring the Potential of Perennial Nectar-Producing Wild Plants for Pellet Combustion. Adv. Sustainable Syst., 2300599, https://doi.org/10.1002/adsu.2023005992024 (2024).
73. Aizen M.A, Harder L.D. Expanding the limits of the pollen-limitation concept: effects of pollen quantity and quality. *Ecolog.*, **88,** 271–281. https://doi.org/10.1890/06-1017 PMID: 17479745 2. (2007).
74. Klein A.M, Vaissiere B E, Cane J H, Steffan-Dewenter I, Cunningham S A, Kremen C, et al. Importance of pollinators in changing landscapes for world crops. *Proceed. Royal Society B: Biol. Sci.*, **274**: 303–313. https://doi.org/10.1098/rspb.2006.3721 PMID: 17164193 (2007).
75. Aizen M.A, Garibaldi L A, Cunningham S A, Klein A M. Long-term global trends in crop yield and production reveal no current pollination shortage but increasing pollinator dependency. *Current Biology*, **18**, 1572–1575. https://doi.org/10.1016/j.cub.2008.08.066 PMID: 18926704 (2008).
76. Garibaldi L.A, Steffan-Dewenter I, Winfree R., Aizen M.A, Bommarco R, Cunningham S A, *et al*. Wild pollinators enhance fruit set of crops regardless of honey bee abundance. *Sci.*, **339**(6127), 1608–1611. https://doi.org/10.1126/science.1230200 PMID: 23449997 (2013).
77. Whitehead, M., Isaac, M.E. Effects of Shade on Nitrogen and Phosphorus Acquisition in Cereal-Legume Intercropping Systems. *Agric.* **2**, 12-24. https://doi.org/10.3390/agriculture2010012 (2012)

78. Carlos de Mola e Silva Neto et al. Bees in agroforestry systems in the Cerrado, *J. Apicultural Res.*, **62**,3 https://doi.org/10.1080/00218839.2021.1907977