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Catch Crops: A Nutrient Reservoir in Post-Harvest Residues under Water Deficit

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Abstract: Undersowing catch crops (CCs) in cereals provides many environmental benefits and potentially contributes to building agricultural resilience to climate change. The increasing soil water deficit due to global warming is becoming a challenge for the sustainability of Central European agriculture. Some of the multiple functions of CCs may be altered under water shortage. Two pot experiments were conducted in Poland to assess the effect of water deficit on N, P, K, and Mg accumulated in post-harvest residues left by spring barley undersown with Italian ryegrass or red clover, and in the soil under these crops. In both experiments, barley grown alone provided a reference, and two levels of water supply were adopted: higher (sufficient for barley) and lower (reduced by 50%). Under water deficit, CCs undersown in spring barley maintained their function of capturing and storing nutrients. Post-harvest residues of barley undersown with CC and stressed with water shortage accumulated the same or higher amounts of N, P, K, and Mg than residues of barley grown alone under sufficient water supply. Soil nutrient contents were negatively correlated with crop biomass. Further research with other CC species and studies based on field experiments under rainout shelters are recommended.

Keywords: intercropping; *Hordeum vulgare* L.; *Lolium multiflorum* Lam.; *Trifolium pratense* L.; water stress; nitrogen; phosphorus; potassium; magnesium

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1. Introduction

Many pathways towards agricultural sustainability, including organic farming, integrated farming, ecological intensification, climate-smart agriculture, and conservation agriculture, promote the cultivation of crops that serve production and environmental/ecological functions [1–5]. Catch crops (CCs) undersown in cereals are one of the best examples of multifunctional crops [6].

The main aim of growing CCs is to prevent leaching of nutrients, mainly nitrogen (N), in the fall after harvest and during the following winter by capturing (catching) and fixing them into living plant tissues [7,8]. An undersown catch crop is a plant sown simultaneously with the main crop (usually cereal species) or during its initial vegetation, which stays after the main crop harvest until fall of the same year or until the following season (over the fall and winter periods) [9]. This form of catch cropping is particularly effective in regions where climatic conditions after harvest of the main crops may reduce the development of late-sown CCs [7]. Grasses and legumes are the most common undersown CCs, and, among them, Italian ryegrass (*Lolium multiflorum* Lam.) and red clover (*Trifolium pratense* L.), respectively, introduced into spring barley (*Hordeum vulgare* L.) field, are particularly prevalent [10–13].

Apart from preventing nutrient leaching, undersown CCs perform other important functions for cropping systems' resilience and long-term stability. Left in the field after harvesting the main crop, they serve as ground covers (cover crops, mulch) and reduce

water and wind erosion [14,15]. When incorporated into the soil, they act as green manure, increasing soil organic matter (carbon) and soil fertility, improving soil structure and water holding capacity, and enhancing soil biological activity [16–18]. Undersown CCs are also valued for suppressing weeds, providing suitable habitat for beneficial fauna (including insect pollinators), and acting as non-host crops for pathogens and pests in the crop rotation [12,13,19]. The participation of legume CCs in symbiotic nitrogen fixation is an additional benefit [20,21]. Recently, the role of CCs, including undersown CCs, has also been emphasized in directly and indirectly lowering greenhouse gas emissions [22,23]. For this reason, catch cropping is claimed to make an important contribution to climate change mitigation [24,25].

Undersown CCs may also be grazed or sold as forage or biofuel raw material [22,26]; however, the economic interest of these crops is rather low [27]. Reimer et al. [28] classify CCs as so-called 'subsidiary crops', i.e., crops grown primarily for their agro-ecological benefits rather than for direct economic profit.

Along with the potential benefits of undersown CCs to farmers, the potential drawbacks of their introduction need to be mentioned, as well. These include increasing costs (purchasing seeds, management operations), making farm management more complex, and the possible reduction in the main (primary) crop yield due to competition of undersown CC for light, nutrients, and soil water [7,12,17,22,27]. These disadvantages seem to be compensated for by the wider benefits [22]. Moreover, the latter can be avoided by selecting species or their mixtures for use as undersown CCs in a way that not only mitigates the effects of competition but allows for interspecific complementary resource use or resource use facilitation [29]. However, to enable farmers to overcome all barriers for the widespread adoption of catch cropping, further research on adapting CCs to specific soil, management, and regional climatic conditions is still needed [22].

The multifunctional ecological potential of undersown CCs is most fully realized when they are grown for mulch or green manure. When they are grazed or harvested for forage or biofuel, much of the biomass and the nutrients it contains are removed from the field. However, nutrient retention and carryover function between phases of a rotation are partially supported by post-harvest residues, i.e., plant roots and the bottom parts of stems, which remain in the field [26].

In recent years, with global climate change, the problem of drought has been growing in many regions of the world [30,31]. This issue also applies to Central Europe, located in a temperate climate [32], where the relevance of drought has so far been underestimated [33]. Rising atmospheric temperatures have increased evapotranspiration rates and exacerbated existing drought conditions originally developed from rainfall deficits during the vegetation period in the region [33]. In addition, seasonal and monthly distributions of precipitation have also been changing [34]. Drying trends have mainly been observed for spring and are less pronounced for summer [33].

The importance of water deficit as one of the key abiotic factors limiting crop development and yields is well recognized [35,36]. Moreover, it can alter the nature of plant-plant interactions, such as intensifying competition [37] or causing a shift from facilitation to competition [38], which also affects the biological productivity of crops [10].

In general, drought reduces the uptake of nutrients from the soil and their transport from the roots to the above-ground parts [36] and affects the nutrient level and distribution in plants [39]. Interspecies interactions between co-existing crops, e.g., the main crop and undersown CC, may also modify nutrient uptake and concentration in the particular plant organs [40,41]. As a result, both water deficit and plant interactions can determine the amount of nutrients removed from the field with biomass and the amount of nutrients remaining in soil and crop residues.

This study aims to assess the effect of water deficit on the amount of nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg) accumulated in post-harvest residues left by spring barley (*Hordeum vulgare* L.) undersown with Italian ryegrass (*Lolium multiflorum* Lam.) or red clover (*Trifolium pratense* L.) and in the soil under these crops.

2. Materials and Methods

2.1. Experimental Design and Conditions

Two separate pot experiments were conducted at a greenhouse laboratory of the Faculty of Biology and Biotechnology, University of Warmia and Mazury in Olsztyn (53°46′47″ N, 20°29′38″ E), Poland. In Experiment I, a pure stand of spring barley (BP) was compared with barley undersown with Italian ryegrass (BR), and, in Experiment II, a pure stand of spring barley (BP) was confronted with barley undersown with red clover (BC). In addition, in both experiments, two levels of plant water supply were established: higher (H) and lower (L) level (water amount). As a result, four treatments were tested in each experiment: BP-H, BP-L, BR-H, BR-L in Experiment I, and BP-H, BP-L, BC-H, BC-L in Experiment II. The basic data for the experiments are presented in Table 1.

Table 1. Basic data for the experiments.

Item	Experiment I	Experiment II
Barley cultivar	Rastik [1]	Rastik
Undersown catch crop (CC), cultivar	Italian ryegrass, Gaza [2]	Red clover, Bona [2]
Plant number in pot		
barley	19	19
barley + CC	19 + 19	19 + 8
Seed planting depth (barley / CC), cm	3/3	3/1.5
Soil type	Cambisols	Cambisols
Soil texture	slightly loamy sand	clay loam
Soil pH, in 1M KCl	6.06	5.80
Average soil content of		
$C_{organic}$, g kg^{-1}	9.1	12.7
N_{total}, mg kg^{-1}	699	823
$P_{available}$, mg kg^{-1}	91	116
$K_{available}$, mg kg^{-1}	196	168
$Mg_{available}$, mg kg^{-1}	30.8	65.7

[1] Hodowla Roślin Smolice Sp. z o. o. Grupa IHAR (Kobylin, Poland), hulless cultivar; [2] Małopolska Hodowla Roślin Sp. z o.o. (Kraków, Poland).

Both experiments were set up according to a completely randomized design in four replications (four pots for each treatment). Each experiment was repeated three times, i.e., three one-year series were performed in consecutive growing seasons (in the months between April and July).

Certified seed/grain material of the first generation (C1) was obtained from Polish seed and breeding companies (Table 1).

Soil material meeting the requirements of the species was taken from the 0–25 cm layer of appropriate cultivated fields at the Research Station in Tomaszkowo (NE Poland, 53°71′61″ N, 20°41′67″ E). It was then crumbled, mixed, slightly air-dried and sieved (a 1 cm mesh sieve; TOYA S.A., Wrocław, Poland) to remove stones, plant remnants, and other impurities.

For the experiments, modified Kick–Brauckmann pots (polyethylene, double-walled, inner part bottomless, exterior part with no drain opening, top inner diameter 22 cm, depth 25 cm; STOMA GmbH, Siegburg, Germany) were used. One week before seed planting, each pot was filled with 8 kg of soil material. The soil medium in the pots was irrigated to a moisture content of about 20% (measured by Time-Domain Reflectometry (TDR), with the use of the FOM/mts meter (Field Operated Multimeter for moisture, temperature, and salinity); E-Test, sole manufacturer of TDR meters and probes designed by the Institute of Agrophysics of the Polish Academy of Sciences in Lublin, Poland), which was maintained until the seeds were sown. Barley and catch crop seeds were planted in pots simultaneously with the use of sowing templates.

Throughout the experiment, the air temperature at the greenhouse laboratory, both day and night, was maintained at 20–22 °C. It was lowered to 6–8 °C for nine days at full

leaf development to support barley vernalization. The air humidity in the greenhouse was maintained at a level of 45–50%. Plants were watered every other day, and the amount of water applied at one time under the higher water supply (H) treatment varied between 100 and 500 mL, depending on the plant development stage. The patterns of plant watering with higher doses were based on earlier, preliminary trials (conducted for each experiment separately) with barley (pure stand) in which plant irrigation requirements during subsequent development stages were established according to the water loss estimated by daily measurements of pot weight. One-time water volumes applied under lower supply (L) were always equal to one-half of the higher volumes. No fertilization or plant protection was used in the experiments.

2.2. Plant Residue and Soil Sampling

All plants were cut 5 cm above the soil surface at the barley maturity stage, and the harvested above-ground biomass was removed and studied further (results not presented here). Post-harvest residues, i.e., plant roots and bottom stem segments, were sampled from each pot. Soil material with plant residues was carefully removed from the pot. Plant residues were separated from the soil by hand sorting and sieving on mesh sieves. Finally, residue biomass was carefully washed out to remove all soil particles. The plant material was then dried at room temperature for several days and weighed.

After separating the plant residues, the sieved soil material collected from each pot was thoroughly mixed and dried at room temperature for several days. Afterwards, plant residue samples (in their entirety) and soil samples (about 300 g) from each pot were used for chemical analyses.

2.3. Plant Residue and Soil Analysis

Chemical analyses of plant and soil material were performed at the Chemical and Agricultural Research Laboratory in Olsztyn, Poland (Accreditation Certificate No. AB 277 issued by the Polish Center for Accreditation in Warsaw) according to standard procedures.

After wet mineralization of plant material in sulfuric acid (H_2SO_4), the total content of nitrogen (N) was determined with potentiometric titration with sodium hypobromite [42], phosphorus (P), by colorimetry with ammonium molybdate [43], potassium (K), by the flame photometric method [44], and magnesium (Mg), by flame atomic absorption spectroscopy [45].

The soil samples underwent determination of the total N content by the Kjeldahl method [46], the available P and K content with the Egner–Riehm method [47,48], and Mg according to the Schachtschabel method [49].

2.4. Calculations and Statistical Analysis

The N, P, K, and Mg accumulation in post-harvest residue biomass was calculated by multiplying the element content by residue biomass from the pot.

The data were submitted to an analysis of variance (ANOVA) or the alternative Kruskal–Wallis test if the analysis of variance assumptions were not met. The normality of variable distribution was checked using the Shapiro–Wilk W-test, and the homogeneity of variance was checked using Levene's test. The differences between objects were assessed using Duncan's test or a multiple comparison test. The relationships between the variables were expressed using simple correlation coefficients. The calculations were performed using Statistica 13.0 software (Dell, Inc., Aliso Viejo, CA, USA).

3. Results and Discussion

3.1. Nutrients in Post-Harvest Residues

The amount of nutrients accumulated in post-harvest residues is a function of the residue biomass left and the nutrient content of that biomass [50]. In the experiments conducted, both BR-H and BC-H plants left a higher biomass of post-harvest residue than B-H plants in Experiments I and II, respectively (Figure 1). These results are not surprising

because, in the present studies, the main part of the post-harvest residue biomass was plant roots, and previous studies show that growing Italian ryegrass or red clover with barley may increase in the field conditions root biomass even several-fold compared with growing barley alone [10,18,51]. This is attributed to the partially complementary use of habitat resources by barley and undersown CCs, or even to the phenomenon of mutual facilitation of resource utilization [52,53]. Although BR-H and BC-H residue biomass from the experiments presented here cannot be compared due to methodological differences, other studies have shown that Italian ryegrass builds both greater above- and below-ground biomass than red clover when they are undersown in barley [10].

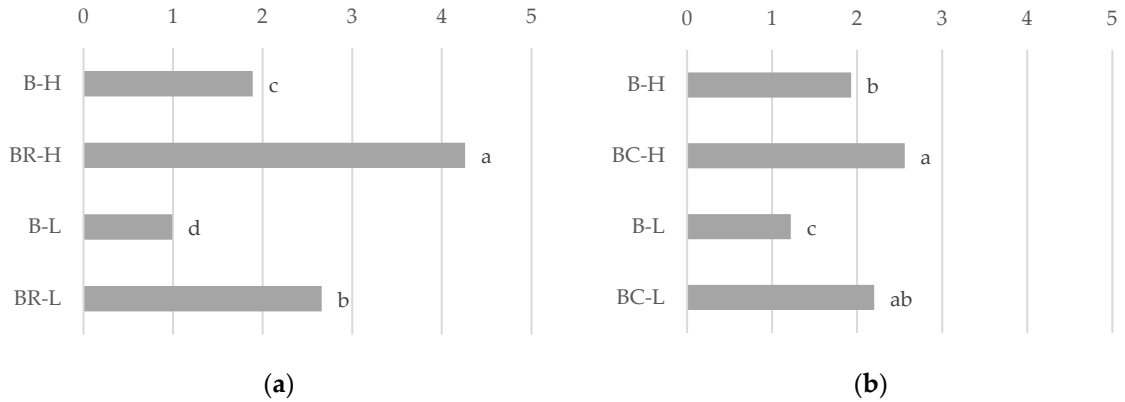


Figure 1. Post-harvest residue biomass, g pot^{-1}: (**a**) Experiment I, with Italian ryegrass as CC; (**b**) Experiment II, with red clover as CC. Different letters next to the bars indicate significant differences at $p < 0.05$.

In Experiment I, water deficit reduced both the residue biomass of B-L plants relative to B-H and of BR-L plants relative to BR-H. However, the biomass of BR-L plant residues was still higher than that of B-L plants. In Experiment II, the post-harvest residue biomass of B-L plants was significantly lower than that of B-H plants, while only a negative tendency was observed for BC-L compared to BC-H.

Leaving aside the different CC plant density in the experiments presented here, in each of them, the reduction in residue biomass of barley with CC under the influence of water deficit was milder than for barley alone. Although barley is thought a naturally drought-tolerant species [54], reduced root biomass in barley under water deficit has also been reported by other authors [55]. Italian ryegrass and red clover are sensitive to water scarcity [56,57] and less competitive than barley [58,59]. Nevertheless, in the present study, when barley reached the ripening stage and finished vegetation (ripening and senescence growth stages; BBCH 83–99 [60]), its competitiveness against CC plants weakened. Thus, during this period, until harvest, CC plants had easier access to limited water and other habitat resources and compensated for the development of their biomass, including the below-ground biomass. The literature indicates that the drought-induced decrease in root biomass is usually less than shoot biomass [55,61]. It was shown by Steynberg et al. [62] that, under water stress, the root system of Italian ryegrass became much deeper to extract water from greater depths.

In Experiment I, there was no effect of water deficit or undersowing barley with Italian ryegrass on the content of N, P, K, and Mg in plant post-harvest residues (Table 2). In contrast, in Experiment II, only the N content was not differentiated by these factors. Higher P content was found in the residues of BC-H plants than in the B-H plant residues. Water deficit increased both the P content in B-L plant residues compared to B-H and in BC-L versus BC-H. The residues of BC-H plants showed a lower K content than those of B-H plants, as did the residues of B-L and BC-L plants, which did not differ from each other or BC-H plant residues in this regard. The Mg content of post-harvest residues was differentiated by undersown red clover, while water deficit did not affect it. As a result, BC-H and BC-L plant residues contained more Mg than B-H and B-L plant residues.

Table 2. Nutrient content in post-harvest residue biomass, g kg^{-1} DM (average ± standard error).

Experiment	Water Supply	Crops	N	P	K	Mg
I	H	B	12.1 ± 0.14 a [1]	2.37 ± 0.03 a	10.7 ± 0.15 a	1.37 ± 0.12 a
		BR	13.0 ± 0.18 a	2.60 ± 0.04 a	11.5 ± 0.15 a	1.47 ± 0.12 a
	L	B	13.9 ± 0.14 a	2.70 ± 0.06 a	11.0 ± 0.22 a	1.70 ± 0.02 a
		BR	10.8 ± 0.22 a	2.80 ± 0.07 a	9.6 ± 0.11 a	1.67 ± 0.02 a
II	H	B	18.5 ± 0.15 a	2.41± 0.01 c	21.6 ± 0.46 a	1.54 ± 0.02 b
		BC	16.5 ± 0.43 a	2.80 ± 0.12 b	18.1 ± 0.47 b	1.97 ± 0.11 a
	L	B	16.5 ± 0.11 a	2.74 ± 0.04 b	17.8 ± 0.59 b	1.66 ± 0.01 b
		BC	17.7 ± 0.13 a	3.15 ± 0.08 a	18.4 ± 0.38 b	2.09 ± 0.03 a

[1] different letters indicate significant differences at $p < 0.05$.

Under higher water supply, the proven differences (or lack thereof) were probably the result of species-specific element contents, interspecific interactions modifying these contents, and the proportion of the organs of barley and CC in the residues. Previous studies have shown that legumes tend to contain more N, P, and Mg and less K than grasses, including cereals [40,63]. Wanic et al. [40] proved that, under the influence of interaction between spring wheat and Persian clover (undersown CC), N content in roots and above-ground parts of wheat decreased, but N content in the organs of Persian clover did not change. In another paper, Wanic et al. [41] reported a strong reduction in K content in wheat and Persian clover under mutual competition, no change in P and Mg content in wheat, but a decrease in P content only in roots and Mg content only in the above-ground parts of Persian clover.

Increased P uptake by cereals accompanied by a legume was reported by Hinsinger et al. [52]. Facilitation of P uptake for the interaction partner is attributed to P release from organic compounds through the action of extracellular enzymes [64], to the release of inorganic P bound in the soil through pH lowering by legumes involved in N_2 fixation [65], or to the P transfer between plants via the hyphae of arbuscular mycorrhizal fungi [66].

Numerous previous studies have shown that, under drought conditions, reduced soil moisture limits nutrient uptake from the soil to the roots and impairs nutrient transport from the roots to the shoots due to a decrease in the transpiration rate, an imbalance in active transport and membrane permeability [36,67,68]. This may decrease nutrient concentration and distribution in plants [39]. Limited uptake from soil may explain the lower K content in B-L residues in Experiment II, and reduced nutrient transport from roots to shoots may correspond with higher P content in residues of B-L and BC-L plants. Some studies indicate that decreases in nutrient concentration in shoots are not attributable to the effects of drought on the translocation of nutrients from roots to shoot [55,69]. There are also opinions that the mineral uptake responses under moisture stress vary across the crop species [68], and the effects of drought on mineral concentration are nutrient-specific [70]. Nutrient relationships also contribute to the complexity of the problem [68]. Bista et al. [55] claim that the more severe the drought, the greater the negative impact on nutrient relations. According to He and Dijstra [67], drought treatments that included drying–rewetting cycles may show no effect on plant nutrient concentrations. Experiment I and some effects from Experiment II (for N and Mg) seem to be consistent with the aforementioned finding.

The combined effects of water deficit and interspecies interactions between main crop and undersown crop on nutrient content in plants, especially in their roots, are not fully explored. Existing research suggests that, even if water deficit intensifies competition between plants, this is manifested in the nutrient uptake/accumulation in biomass (mostly linked to biomass volume). Its content tends to be unaffected by the interaction of these stress factors [71].

None of the experiments found a significant correlation between the N, P, and K content of the crop residues and the residue biomass. However, both experiments reported a positive correlation for Mg (simple correlation coefficients were 0.781 and 0.499 for Experiments I and II, respectively). In the literature, the effect of nutrient dilution/concentration

along with an increase/decrease in plant biomass is usually described [72,73]. However, this phenomenon seems to be determined mainly by above-ground biomass [74]. In a study by Ciećko et al. [74], the Mg content in the roots of oats, maize, yellow lupine, and radish positively correlated with plant root biomass (similarly to the present research, where roots are the main part of crop residues), while the content of this element in the above-ground parts mostly correlated negatively with plant above-ground biomass.

In Experiment I, twice, or more than twice, as much N, P, K, and Mg were accumulated in BR-H plant residues than in those of B-H plants (Figure 2). Compared with B-H plants, B-L plants decreased the amount of N accumulated in post-harvest residues, tended to reduce P and K accumulation, and did not change Mg accumulation. Water deficit reduced the accumulation of N, P, K, and Mg in BR-L plant residues compared to the BR-H plants. However, the accumulation of these nutrients in BR-L plant residues was substantially higher than in those of B-L plants (twice or more) and statistically the same (N, P, K) or higher (Mg) than in B-H plant residues.

In Experiment II, more N was accumulated in BC-H plant residues than in B-H plant residues, while the amounts of P, K, and Mg in BC-H and B-H residues were the same. Water deficit was the cause of reduced N and K accumulation in the residue of B-L plants compared to B-H plants, without causing a significant change in P and Mg accumulation (only a decreasing tendency was noted). Moreover, when compared to BC-H plants, only lower N accumulation and no change in P, K, and Mg accumulation were observed in the residues of BC-L plants under water deficit.

In both experiments, the amounts of N, P, K, and Mg accumulated in post-harvest residues were positively correlated with residue biomass (Table 3). A positive correlation of nutrient accumulation with nutrient content was found for Mg in Experiment I and for N, P, and Mg in Experiment II. The stronger dependence of nutrient accumulation in plant biomass on biomass volume than on biomass nutrient content is not unexpected [71,75].

Table 3. Dependence of nutrient accumulation on nutrient content and post-harvest residue biomass volumes, simple correlation coefficients.

Experiment	Post-Harvest Residue	N	P	K	Mg
I	biomass	0.985 [1]	0.998	0.980	0.991
	nutrient content	ns	ns	ns	0.847
II	biomass	0.862	0.964	0.962	0.958
	nutrient content	0.464	0.400	ns	0.686

[1] values significant at $p = 0.05$; ns—no significance at $p < 0.05$.

3.2. Nutrients in the Soil

In both experiments, decreases in the contents of total N and available P, K, and Mg in the soil were typically found compared to the starting situation. However, there were also a few exceptions in which these changes were statistically insignificant (Table 4).

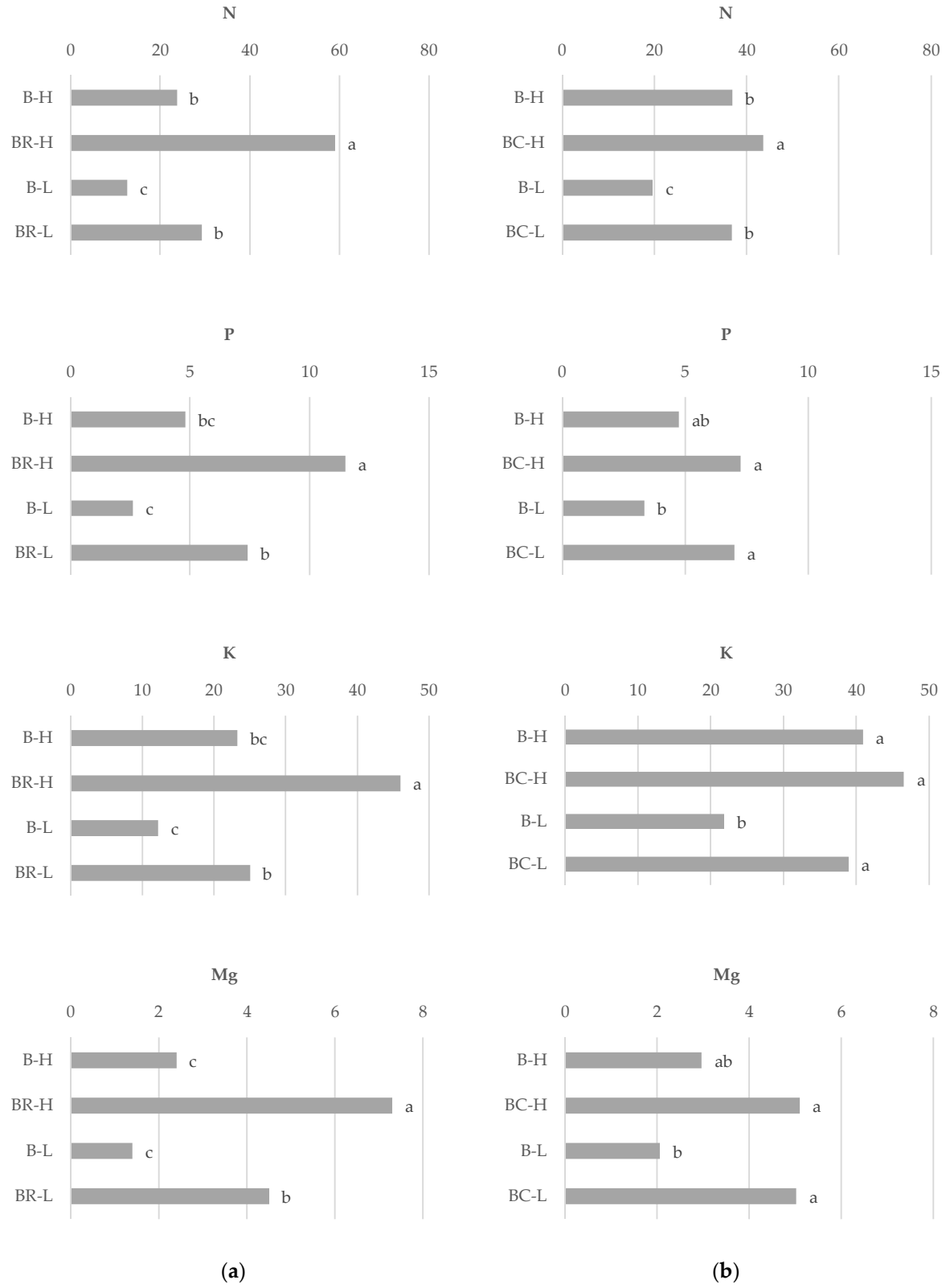


Figure 2. Nutrient accumulation in post-harvest residue biomass, mg pot^{-1}: (**a**) Experiment I, with Italian ryegrass as CC; (**b**) Experiment II, with red clover as CC. Different letters next to the bars indicate significant differences at $p < 0.05$.

Table 4. Nutrient content in soil, mg kg^{-1} DM (average ± standard error).

Experiment	Water Supply	Crops	N	P	K	Mg
I	H	B	667 ± 48 ab↓ [1]	87 ± 4.4 a	132 ± 5.8 ab↓	29.7 ± 1.45 a
		BR	643 ± 44 b↓	86 ± 4.3 a	116 ± 7.8 b↓	28.7 ± 1.06 a↓
	L	B	683 ± 67 a	88 ± 6.4 a	150 ± 6.1 a↓	30.0 ± 0.91 a
		BR	643 ± 33 b↓	85 ± 5.3 a	126 ± 6.9 ab↓	28.7 ± 0.66 a↓
II	H	B	587 ± 44 b↓	89 ± 5.7 b ↓	109 ± 5.9 b↓	55.7 ± 1.76 b↓
		BC	690 ± 40a↓	98 ± 5.6 ab↓	106 ± 7.4 b↓	57.7 ± 1.20 ab↓
	L	B	705 ± 50 a↓	103 ± 7.0 a↓	132 ± 2.9 a↓	61.3 ± 0.67 a
		BC	680 ± 25 ab↓	101 ± 7.8 ab↓	130 ± 6.6 a↓	60.7 ± 0.88 a↓

[1] different letters indicate significant differences at $p < 0.05$; ↓ (arrows) indicate significant decrease in relation to the starting state.

In Experiment I, no changes in soil P and Mg content were proved under the influence of water supply and undersowing barley with Italian ryegrass, and the changes in N and K content should be considered as a tendency rather than a regularity. A general tendency was observed for a stronger depletion of soil N and K by barley undersown with Italian ryegrass and for a weaker reduction in these elements by plants under water deficit conditions. Significantly lower soil N content was found under BR-L than under B-L, and no differences were observed between soil N content under BR-H and BR-L plants.

In Experiment II, the least amounts of N, P, and Mg were left in the soil under B-H plants. Significantly higher N content and a tendency for higher P and Mg content was observed under BC-H plants. Water deficit promoted higher N, P, and Mg contents in soil under B-L relative to B-H, while it was less pronounced on soil content in soil under BC-L plants relative to BC-H. The K depletion from the soil was reduced only by water deficit, while undersowing barley with red clover was not significant in this respect.

In both experiments, the observed changes in the soil nutrient contents should be primarily attributed to the nutrient uptake by plants and their accumulation in the produced larger or smaller biomass. In the case of N in Experiment II, red clover participation in biological N_2 fixation (death and decay of nodules and roots, N-compounds exuded by legume roots and nodules) [76,77] and its reduction under the influence of water deficit [78,79] also need to be considered.

In Experiment I, a strong negative correlation between N, K, and Mg content in the soil and the biomass of post-harvest residues and harvested/removed above-ground biomass was proven (Table 5). Therefore, the loss of these nutrients from soil was determined by their accumulation in the removed biomass and in the biomass left in the pots, the latter being of even greater importance. An insignificant or weaker relationship with removed biomass and post-harvest residue biomass, respectively, was found for soil P content, which may be related to the increased solubility of P bonded with aluminum (Al), iron (Fe) and manganese (Mn) through the intense secretion of organic acids [80] by the abundant root system of Italian ryegrass plants [10]. For this reason, the decrease in soil P content compared to the starting situation may have been negligible for statistical analysis.

Table 5. Correlation between soil nutrient content and crop biomass removed (harvested) and the biomass of post-harvest residues.

Experiment	Biomass (of)	N	P	K	Mg
I	removed	−0.657 [1]	ns	−0.855	−0.632
	post-harvest residues	−0.880	−0.593	−0.947	−0.874
II	removed	−0.586	−0.915	−0.906	−0.972
	post-harvest residues	ns	ns	−0.540	ns

[1] values significant at $p = 0.05$; ns—no significance at $p < 0.05$.

In Experiment II, nutrient contents were negatively correlated with the amount of harvested/removed plant biomass. A particularly strong inverse relationship was recorded for P, K, and Mg. An increase in soil N content can explain the slightly weaker relationship in the case of N as a result of biological N_2 fixation involving red clover [76]. The relationship of soil N, P, and Mg content with post-harvest residue biomass was not confirmed, which may be due to the high predominance of biomass removed to that left as crop residues. In contrast, significantly less K was left in the soil also when the residue biomass increased. This may be due to higher K uptake by plants than P, Mg, and even N [81–83], as well as more intensive K accumulation in roots (in symplast vacuoles), than observed for other nutrients [84].

4. Conclusions

Although water deficit hindered plant development, Italian ryegrass and red clover undersown in spring barley maintained their function of capturing and storing nutrients. Post-harvest residues of barley undersown with CCs and stressed with water shortage provided a more abundant repository of N, P, K, and Mg than the residues of barley grown alone under these conditions. Moreover, they accumulated the same or higher nutrient amounts than residues of barley grown alone under sufficient water supply. The effect of water deficit on soil nutrient content was manifested by lower nutrient depletion due to uptake by the smaller plant biomass produced. Considering the limitations of pot experiments, further field studies under rainout shelters are recommended, along with expanding the CC species spectrum.

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