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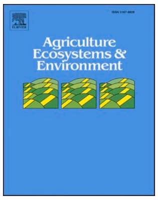

Reduced weeding shows potential to regulate nutrient leaching in a cabbage (*Brassica oleracea*, var. capitata) lysimeter trial

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ABSTRACT

Agricultural land is the main contributor to nitrogen and phosphorus pollution of groundwater sources. Adopting agroecological management practices can support the transition towards sustainable farming systems. We investigated if reduced weeding could support nutrient retention in a nutrient demanding vegetable crop (*Brassica oleracea*, var. capitata), without causing unacceptable yield losses. We conducted a three-year study (2019–2021) with two cropping seasons (autumn and spring) using 1 m^3 above-ground lysimeters, each containing four cabbage plants. Different vegetation covers, each with four replicates, were considered: 1) crop only 2) weeds only 3) crop + weeds from crop transplanting 4) crop + weeds after 20 days from crop transplanting 5) bare soil with fertilizer 6) bare soil without fertilizer. Each system received the recommended dose of mineral fertilizer for cabbage (130 kg ha^{-1} N, 80 kg ha^{-1} P, 150 kg ha^{-1} K), except for two bare soil lysimeters which were not fertilized. Water samples were taken throughout the growing season, in particular after each fertilization event, and analysed for nitrate (NO_3-N), phosphorus (P) and potassium (K) concentrations. Cabbage yield in both weedy treatments was significantly lower compared to the weed-free plots only in spring 2020 and fall 2021. Weed cover contributed to explain NO_3-N and K leaching, while P leaching was affected by crop cover. The results suggest that it is possible to reduce weed management intensity in cabbage while also obtaining some benefits concerning nutrient losses.

1. Introduction

Plant nutrition is a fundamental component of crop production. The development of nitrogen-based mineral fertilizers has greatly increased the efficiency of nutrient uptake by ensuring rapid absorption of macro- and micro-nutrients by plants. However, the simplification and specialization of cropping systems has led to an extensive use of inorganic fertilizers (Li et al., 2018). The excess of nutrients which plants cannot capture is lost through air and waterways causing major environmental and health issues (de Boer, 2017; Lentz and Lehrsch, 2018).

Most drinking water supplies come from treated groundwater sources, which are thus safeguarded by many countries primarily from nitrate (NO_3-N) and phosphorus (P) pollution (Colombani et al., 2020; Eder et al., 2015; Hansen et al., 2011). For this reason, the European Union has put a threshold of 50 mg L^{-1} of nitrates in aquifers (Kühling et al., 2020).

Phosphorus can be quickly fixed to soil particles, thus reducing its mobility compared to nitrate (do Nascimento et al., 2018). Nonetheless, oversupply of phosphorus in P-rich soils causes a vertical dispatchment from the topsoil beyond the rooting zone, even in clay-rich soils (Azevedo et al., 2018; von Wandruszka, 2006). Additionally, high nitrate pollution is directly linked to high P losses leading to eutrophication (Kokulan et al., 2022).

In a report focussed on P losses, Amery and Shoumans (2014) concluded that the water quality in Europe was considered poor across several countries. Kronvang et al. (2007) found the highest contributor of P losses across several European catchments to be from agricultural land. Despite this, there is no official EU legislation on P limits in waterways. To the knowledge of the authors, only Ireland has put a threshold for P in groundwater (0.03 mg L^{-1}) (EPA, 2020).

These limitations are especially necessary since only 40% and 46% of applied N and P respectively are incorporated in harvested products (Biswas Chowdhury and Zhang, 2021; Lentz and Lehrsch, 2018).

Nutrient leaching depends on an array of factors including climate,

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soil texture, pH, water table depth and land use (Alfaro et al., 2006; Li et al., 2018; Olesen et al., 2019). Due to the diversity of these parameters in Europe, each country adopts its own legislation (Zavattaro et al., 2012).

In Italy 17% of N surplus is lost in groundwater and small water bodies (Velthof et al., 2009). Most of the losses from agricultural land are concentrated in the Po valley, which passes through three of the largest regions in Italy where most of the livestock production is concentrated (Zavattaro et al., 2012). The Nitrates Directive (91/676/EEC)(Musacchio et al., 2020) enforces limitations of fertilizer use by acting on optimizing fertilizer efficiency or timing of slurry burial (Perego et al., 2012). For this reason, most studies on nutrient leaching focus on the effect of soil type and climate, or on the response to different irrigation and fertilizer inputs (Eder et al., 2015; He et al., 2017; Li et al., 2018).

Several agricultural practices can be used to reduce fertilizer losses. Ranging from better fertilizer synchronization to more agroecological practices such as the use of catch crops during the winter months. Constantin et al. (2010) performed a 13-year experiment in which they found that catch crops were more efficient than reduced N fertilization at containing N losses in both maize and sugar beet cropping systems.

Large-scale vegetable cropping systems often receive excess water and nutrient inputs to boost yields and product quality (Li et al., 2018). Furthermore, frequent soil disturbances are applied in horticultural systems. In addition to high input use, soil disturbances increase nutrient losses. It is therefore necessary to consider actions to favour conservative agricultural practices in vegetable cropping systems. Despite this, the role of diversified ground cover in reducing nutrient loss has been scarcely addressed in horticulture (Allende-Montalban et al., 2022; Hauggaard-Nielsen et al., 2003; Marcos-Pérez et al., 2023).

Ground cover in vegetable systems can be obtained in several ways. Few studies have tested the use of living mulches, obtained by sowing species that coexist with the main crop, aimed at providing ecosystem services such as weed control, erosion control and reduction of nutrient leaching (Leoni et al., 2020; Ponti et al., 2007; Razze et al., 2016). The drawback of this approach is the cost of buying and sowing the intercrop and managing it subsequently. A recent review suggested that spontaneous weed vegetation can also contribute to soil-related ecosystem services among which nutrient leaching (Blaix et al., 2018). Spontaneous vegetation associated to no tillage or minimal weeding practices may be an important contributor in minimizing nutrient losses (Yagioka et al., 2015). The advantage of this approach is that farmers have no additional management cost while also reducing the cost related to weed management. However, the benefits associated to reduced weed control are only welcomed if the acceptable yield loss threshold (between 2% and 5%) is not exceeded (Knezevic et al., 2002). To date information is missing about weed management regimes that can limit competition with the crop while providing ecosystem services (Virili and Moonen, 2022). Cabbage is known to be sensitive to weed competition in the first 20 days after transplanting (Weaver, 1984). It may therefore be possible to accept weeds in the crop later in the growing season, taking advantage of the weeds' capacity to intercept excess nutrients, especially in the rainy season. Therefore, it is necessary to assess the extent to which weeds can be tolerated under specific management types given the potential benefits.

We performed a lysimeter experiment to investigate the role of weeds in regulating the permanent loss (i.e., when nutrients surpass the rooting zone and percolate into the groundwater) of the primary plant macronutrients. Lysimeters are commonly used to follow the fate of water, nutrients or contaminants in semi-closed systems which simulate field conditions while allowing to control important factors of variability, such as soil type and depth (Hansen et al., 2000). Nitrogen and phosphorus loss pathways have received the most attention, but potassium (K) should also be accounted for when considering the fate of macronutrients (Griffioen, 2001; Kolahchi and Jalali, 2006). Although the environmental impact of potassium leaching is still unclear, some EU countries have set thresholds for K in waterways. Poland has indicated a range of 8–31 mg L^{-1} of acceptable K in groundwater, while Belgium has set the threshold at 15 mg L^{-1} (EUR-Lex, 2014). Furthermore, Velthof et al. (2009) mentioned that a decrease in the emission of one pollutant may increase the emission of another pollutant. This was also investigated by Lawniczak et al. (2016), who suggested that reducing the fertilizer level of one of the macronutrients may not reduce the overall leaching but may aggravate pollution due to unfavourable N:K and N:P ratios in soils.

We aim to provide a comprehensive view of the trade-off associated to implementing reduced weeding in a cabbage (*Brassica oleracea*, var. *capitata*) cropping system, weighing the value of the service provided against potential yield loss. Cabbage was chosen as the focal crop because it is, like many leafy greens, nutrient demanding and is preferably grown in sandy soils to favour root development and nutrient absorption after transplanting. Although cabbage can be grown year-round, in the northern hemisphere it is typically considered an autumn vegetable (Cervenski et al., 2022), so the main growing cycle coincides with the rainy season when the cropping systems are prone to nutrient leaching.

We expected a critical weed-free period of 20 days from crop transplanting to guarantee crop yield at the cost of reduced leaching regulation due to slower weed development. We hypothesized that leaching would be lowest in the weedy control plots, since the service provided by the added vegetation cover was expected to be highest at the first rainy event after fertilizer application.

2. Materials and methods

2.1. Experimental site description

The experiment was carried out at the Agro-Environmental Research Centre of the University of Pisa, Italy (43.66258, 10.34837). A battery of twenty aboveground polyethylene cubic lysimeters (1 m x 1.2 m by 1 m height) were filled with soil from the north of Italy ("Italiana Terricci"; Gruppo Valagussa, Lecco) separated by a net from a bottom layer of pebbles and expanded clay (Pistocchi et al., 2017). The lysimeters were filled with soil in February 2019 and were left untouched until September 2019. The external walls of each lysimeter were covered with insulating material. Drainage water was collected in plastic 30 L tanks connected to the bottom of the lysimeters with a polyvinyl tube.

Prior to the first cropping season (autumn 2019) three soil cores of 0–30 cm depth were taken from each lysimeter to obtain general soil properties. Soil was mainly sandy (76.3%) with 9.4% clay; total soil N was 1.02% with 2.3% of organic matter and C:N ratio of 13.1; pH was 8.2. All percentages refer to dry matter.

The cabbage (*Brassica oleracea var. capitata*) cultivar chosen for the trial was the day-neutral "Famosa", which has a cropping cycle of 70–80 days and can be grown year-round. The trial was replicated three times in the fall (2019–2021) and twice in the spring (2020–2021).

The average annual rainfall and air temperature of the area during the duration of the trial were 81.3 mm and 15.4 °C, respectively (see Fig. 1).

Each lysimeter contained four cabbage plants transplanted at 5 weeks after sowing in a 0.50 m by 0.50 m grid, leaving a 0.25 m and 0.35 m border from the inner walls of the lysimeter. Treatments were arranged in a completely randomized design. Different vegetation covers were considered: 1) weed-free control (C) 2) weeds only (W) 3) crop + weeds kept from the beginning of the growing season (CW) 4) crop + weeds allowed to grow after 20 days from crop transplanting (C20) 5) bare soil without fertilizer 6) bare soil with fertilizer. The lysimeters with vegetation cover were replicated four times, while the bare soil lysimeters were replicated two time each and served as controls for data collection of water and soil parameters. Each treatment received the recommended dose of mineral fertilizer for cabbage grown in sandy soils (130 kg ha^{-1} N, 80 kg ha^{-1} P_2O_5, 150 kg ha^{-1} K_2O). Fertilizer was

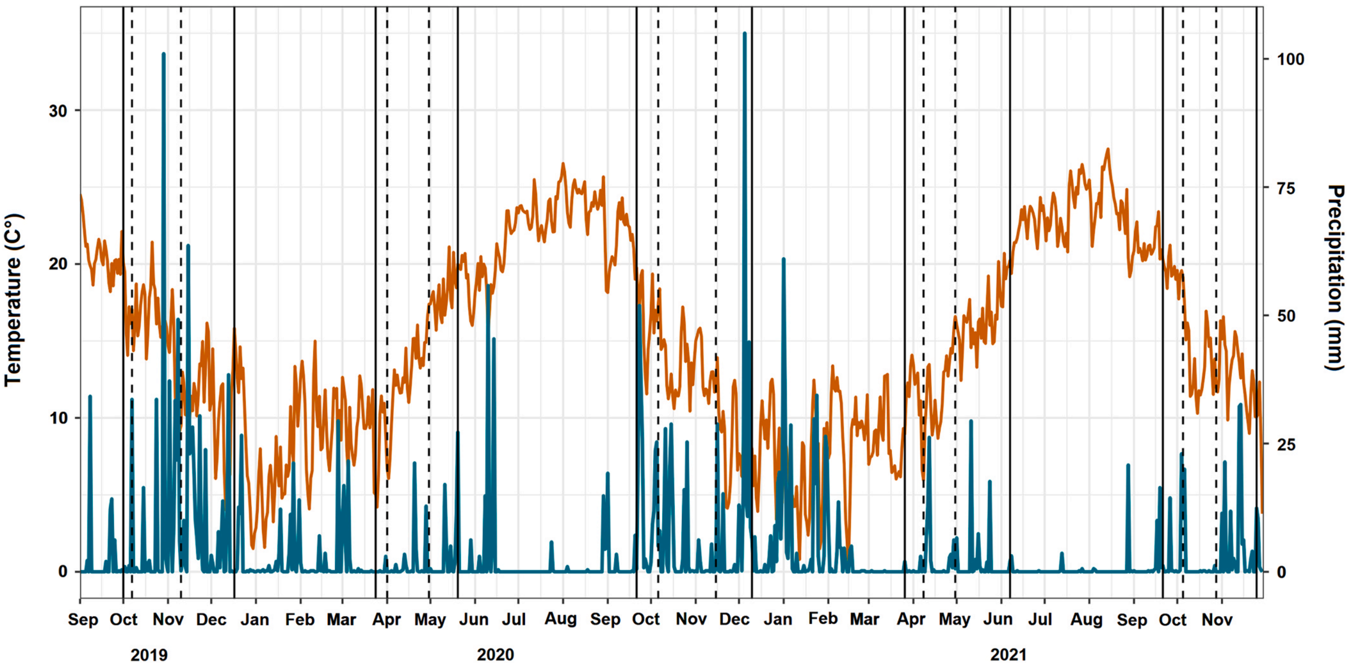

Fig. 1. Average temperature and precipitation during the three years the lysimeter trial took place. Solid vertical lines represent the start and end of each cropping season. Dashed vertical lines indicate dates of fertilizer application.

applied at two times: 1) 50% of the total dosage of N and the full dosage of P and K at transplanting 2) the remaining 50% of N at head formation. White mustard (*Sinapis alba, L.*) was sown as a model weed species to standardize the weed community in all lysimeters (except in autumn 2019), at a density of 20 plants m^{-2}. All plots were hand-hoed two weeks prior to transplanting and mustard seeds were sown one week before crop transplanting in the weedy control plots. In the plots which were left weed-free for the first 20 days, mustard seeds were planted 10 days after transplanting. Plots which were kept weed-free were hand-hoed every week.

2.2. Data collection

After crop transplanting, water samples were taken after each rain event and after each fertilizer application. The volume of total percolated water was collected in tanks positioned at the base of the lysimeters, the containers were then weighed and emptied after each water sampling collection or when they were about to reach full capacity (30 L). For sampling dates in which only the volume of drained water was collected, nutrient data were interpolated by averaging values from the previous and following sampling dates (Table 1). The cabbage system was rainfed, but in prolonged dry periods irrigation was provided to meet cabbage requirements (ca. 10 mm week^{-1}). Water was tested for nitrates (method: spectrophotometry with salicylate) (Cataldo et al., 1975), total phosphorus (method: spectrophotometry with molybdate; APAT CNR IRSA Man 29 2003 – 4110 A1), and soluble potassium (atomic emission spectrometry; APAT CNR IRSA Man 29 2003–3240 A).

At harvest, each cabbage plant was weighed for crop total fresh biomass and marketable biomass. Crop and weeds were then oven-dried at 60 °C for 72 hours and weighed for dry biomass.

2.3. Data analysis

Soil and water samples were taken from each lysimeter prior to crop establishment. Soil analyses were performed before crop transplanting and after crop harvest from the 0–30 cm soil layer (three cores per lysimeter) to determine nitrates (Eaton and Clesceri, 1995), phosphorus (Olsen and Sommers, 1982) and potassium (Gessa and Ciavatta, 2000). The effect of weeding regime on cabbage fresh marketable biomass (i.e., yield) was tested using a linear model with the "lm" function in the

Table 1
Cropping season information and dates of water sample collection in the lysimeter study. In bold are dates in which only water volume was collected and the nutrient concentration values were interpolated using the average between the previous and following date.

	Autumn			Spring	
	2019	2020	2021	2020	2021
Start – End of Cropping Season	1st October – 17th December	21st September – 10th December	21st September – 25th November	26th March – 20th May	24th March – 7th June
Total Precipitation (mm)	705.2	673.2	227.9	90.8	141.2
# Rainy Days	46	55	32	22	30
Mean Temperature (°C)	13.6	12.4	14.5	14.2	16.5
Mean Min Temperature (°C)	9.3	8.1	9.3	7.6	7.6
Mean Max Temperature (°C)	18.0	18.1	20.6	21.1	20.3
Water Sample Collection Dates	1/10; 16/10; 25/10; 04/11; 14/11; 19/11; 25/11; 09/12; 16/12	29/09; 05/10; 15/10; 19/10; 28/10; 06/11; 17/11; 23/11; 04/12; 09/12; 12/12	06/10; 15/10; 28/10; 08/11; 22/11	03/04; 23/04; 30/04; 15/05	07/04; 15/04; 23/04; 30/04; 10/05; 26/05

"lme4" package (Bates et al., 2015) followed by an Analysis of Variance with the function "Anova" in the "car" package (Fox and Weisberg Sanford, 2019). Weeding regime, season and year were included as explanatory variables in the model. Models were validated with the "simulateResiduals" function in the "DHARMa" package which uses a Kolmogorov-Smirnov test to detect significant deviation and outliers (Hartig, 2021). A post-hoc Tukey test was then performed with the function "emmeans" in the package "emmeans" (Lenth, 2021).

Leached nutrient concentrations were flow-weighed by multiplying the concentration by the volume of water drained at each sampling date (Li et al., 2018). The effect of weed cover on nutrient leaching was analyzed with generalized least squares (GLS) mixed effects models (MEM). This model was chosen after confirming the non-homogeneous variance of the data (Gałecki and Burzykowski, 2013). Models were run using scaled data. For each nutrient the weights and random structure were selected referring to a full model, containing crop cover, weed cover, growing season (GS), volume of drained water and all of the interactions between fixed factors. Firstly, the full models were weighted differently for each dependent variable, to address the variance variability in each nutrient. The GLS models with the modelled variance were tested against the same full models with homogeneous variance, thus the best model was selected. The GLS model was then tested against a model containing a random structure ("random = ~1|lysimeter/GS"). The model with the random structure had the lowest AIC and thus was selected (Zuur et al., 2009). Finally, model selection was performed for each response variable. The main interest of this study was to assess whether weed cover increased the strength of the model.

Finally, we performed model selection starting from an "a priori" model containing crop cover, GS and drained water together with their interactions, with the selected random structure and weights for each response variable. This null model was tested against other nine models containing weed cover, alone or with the different weed interactions (Table 4). In this way we tested ten different hypotheses on the effect of weed cover on each response variable (Anderson and Burnham, 2002; Johnson and Omland, 2004). The ten hypotheses for each response variable were compared based on AIC value. This resulted in a unique model for each nutrient, with the same random component. The models were validated by checking distribution and homogeneity of residuals, as for the linear models. No post-hoc test was performed in this case. This decision is supported by Qian and Miltner (2018) who explain that for datasets with a small sample size or with large natural variability (such as in our case) p-values are also highly variable, leading to unstable tests. Moreover, mixed effects models fall under the umbrella of multilevel models, which inherently address the multilevel comparison problem as they perform partial pooling of the estimates towards a common mean (Gelman, 2006). All statistical analyses were performed using R (v. 4.1.0) (R Core Team, 2021).

3. Results

3.1. *Effect of weeding regime on cabbage fresh marketable biomass*

A significant interaction between weeding regime, season and year was found ($p<0.0001$) (Table 2). In spring 2020 and fall 2021 both C20 and the weedy control yielded less than the weed-free control. In spring 2021 weedy control yielded less than both weed-free control and C20 (Table 3).

Table 3

Significant arithmetic differences in mean fresh marketable biomass (g m^{-2}) between weeding regimes from the Tukey HSD post-hoc test in the lysimeter trial. Effect was considered significant at the $p<0.05$ level.

		Autumn			Spring	
	Weeding regime	*2019*	*2020*	*2021*	*2020*	*2021*
Fresh Marketable Biomass	*Weed-free*	191.6 ± 13.6 *a*	188.2 ± 19.1 *a*	222.7 ± 30.6 *a*	598.5 ± 54.3 *a*	282.8 ± 21.9 *a*
	Weed-free (20 days)	160.4 ± 11.5 *a*	235.6 ± 12.6 *a*	115.9 ± 44.7 *b*	378.8 ± 29.9 *b*	195.7 ± 21.2 *a*
	Weedy	173.0 ± 14.2 *a*	197.6 ± 8.3 *a*	113.2 ± 20.1 *b*	298.0 ± 9.7 *b*	93.1 ± 35.0 *b*

3.2. *Effect of weeding regime on nutrient leaching*

A summary of the model selection for each response variable is available in Table 4. Each response variable was explained by a unique model.

In the case of nitrate leaching the inclusion weed cover in the model improved the explanatory capacity when included in the interaction with each of the base fixed variables. In particular, including the

Table 4

Comparisons of 10 linear models for nitrate, phosphorus and potassium leaching volumes (mg L^{-1}). The Akaike Information Criterion (BIC) was used as a tool for model selection. The factors tested in the model were: crop cover "Crop", the volume of drained water "Drain", the growing season "GS", and weed cover "Weed". The selected models with the lowest AIC are underlined for each response variable.

Model	NO_3-N		P		K	
	AIC	DF	AIC	DF	AIC	DF
Model 1 (Crop:Drain:GS)	-547.77	58	**647.01**	**27**	-167.94	27
Model 2 (Crop:Drain:GS) + Weed	-546.03	59	648.92	28	-166.55	28
Model 3 (Crop:Drain:GS) + Weed+ Weed:Crop	-544.63	60	650.91	29	-166.35	29
Model 4 (Crop:Drain:GS) + Weed + Weed:GS	-552.07	63	653.44	32	-188.16	32
Model 5 (Crop:Drain:GS) + Weed + Weed:Drain	-548.79	60	650.75	29	-189.02	29
Model 6 (Crop:Drain:GS) + Weed + Weed:Drain + Weed:GS + Weed:Crop	**-553.36**	**65**	656.43	34	-203.75	34
Model 7 (Crop:Drain:GS) + Weed+ Weed:Drain+ Weed:GS + Weed:Crop + Weed:Crop:GS	-552.23	69	660.61	38	-211.21	38
Model 8 (Crop:Drain:GS) + Weed + Weed:Drain + Weed:GS + Weed:Crop + Weed:Crop:Drain	-552.60	66	658.28	35	-201.75	35
Model 9 (Crop:Drain:GS) + Weed + Weed:Drain + Weed:GS + Weed:Crop + Weed:GS:Drain	-549.73	69	661.71	38	**-273.01**	**38**
Model 10 Crop:Drain:GS: Weed	-542.87	78	670.17	47	-270.06	47

Table 2

Effect of weeding regime on cabbage dry total, fresh total and fresh marketable biomass (g m^{-2}). Effect was considered significant at the $p<0.05$ level. * $0.01<p<0.05$; ** $0.001<p<0.01$; *** $p<0.0001$; "n.s."=not significant.

Cabbage fresh marketable biomass	Treatment (T)	Season (S)	Year (Y)	T*S	T*Y	S*Y	T*S*Y
F-value:	27.21	73.25	46.68	14.30	0.21	34.92	8.45
p-value	<0.0001	<0.0001	<0.0001	<0.0001	0.92	0.0001	0.0007

interaction between weed cover and growing season greatly improved the model's AIC (Table 4). In fall 2019, NO3-N leaching increased with increasing crop and weed cover (Fig. 2). The final crop yield in that season was average compared to the other growing seasons (Table 3) and rainfall was not different from the 2020 fall season (Table 1). In the other seasons both crop and weed cover contributed in a complementary way to the reduction of nitrogen leaching, with a steeper slope observed in the last two growing cycles.

Potassium leaching estimates were also better represented when weed cover was included in the model, which was greatly improved when the third-level interaction between weed cover, growing season and drained water volume was included. Similarly to nitrate, K trends were also positive in fall 2019 as the growing season progressed. No apparent variations were observed in spring 2020 and negative slopes were found in 2021 and in fall 2020 (Fig. 3B). In general, lower potassium losses were associated to lower volumes of drained water, although in fall 2020 weed cover reduced K amounts in groundwater even at higher percolated water volumes ($\geq$ 30 L).

Only for phosphorus the presence of weed cover in the model did not provide additional information, whereas the response was mainly explained by the interaction between crop cover, growing season and volume of drained water (Fig. 3 A). Similarly to potassium, in fall 2020 higher crop cover reduced P amount in groundwater even at higher percolated volumes. A greater effect of crop cover in reducing phosphorus losses was observed in 2021 and in fall 2020, whereas no apparent variations were found in fall 2019 and in spring 2020.

4. Discussion

The results from the present study originate from a multi-year lysimeter trial for which abundant data were collected. The main result of this study confirmed the hypothesis that increased ground cover can reduce permanent nutrient loss in both fall and spring. The only exception was represented by 2019 because leaching trends were anomalous compared to the expected and observed trends in all other growing seasons. Fall 2019 was the first growing season of our trial and the rainiest out of all the growing seasons, which possibly aggravated the nutrient losses from the initially nutrient rich soil (initial soil organic matter average of 2.3%) which had been allowed to settle for six months and was never cultivated.

With respect to nitrate and potassium, both weed and crop cover played a significant role in reducing leaching. In fall 2020 nitrate concentrations in groundwater from the weedy plots were below 50 mg L^{-1}, as opposed to NO_3-N concentrations from the weed-free plots which were consistently higher than the threshold. In fall 2019 groundwater from all plots was considered highly polluted. On the other hand, in both springs and in fall 2021, NO_3-N concentrations in the groundwater samples from all of the plots were below the WHO threshold. Despite this, it is worth noting that in spring 2020 the effect of weed cover was stronger compared to crop cover in reducing estimated nitrate losses. Several studies have found that, at the same level of fertilization, significantly different nutrient losses were recorded for different water input levels (Bohman et al., 2020; Gheysari et al., 2009; Li et al., 2018). Moreover, plant N uptake was on the lower side, around 20 kg ha^{-1} (data not shown), in relation to the amount of fertilizer supplied each season. This is considerably lower compared to the N in cabbage plants grown by Reza et al. (2016) which was around 130 kg ha^{-1}, although the difference in marketable yield was also ten-fold. Low amounts of nutrient uptake by the vegetation coupled with high water input can aggravate leaching compared to an equal uptake at lower water input levels (Chen et al., 2018; Li et al., 2018; Quemada et al., 2013). The present study used white mustard (*Sinapis alba, L.*) as a dominant species to standardize the weed community in each lysimeter. Non-legume forbs have proven to be useful in reducing permanent nutrient loss through higher N uptake (McLenaghen et al., 1996; Scherer-Lorenzen et al., 2003). Furthermore, this choice was made because we intended to investigate multiple agro-ecosystem services offered by dominant broadleaf weeds in the area and because mustard was not able to disperse its seeds by crop harvest, making randomization of the treatments between years much more manageable. Nonetheless, it is documented that grasses are much more efficient catch crops than forbs (Leimer et al., 2015; McLenaghen et al., 1996).

If the number of lysimeters had allowed it, an optimal experimental design would have been to investigate the effect of weed communities dominated by grasses versus communities dominated by forbs in reducing nutrient leaching, weighed against potential yield reduction. Despite our restrictions we obtained important preliminary results which should be used as a starting point for future, more complex studies and will contribute to discussions on this important topic. On a similar note, there is evidence for the fact that diversified weed communities can effectively reduce nitrate leaching (Leimer et al., 2015) while being less competitive towards crops (Adeux et al., 2019; Esposito et al., 2023). Investigating this topic would provide further evidence on the multifunctionality of diverse weed communities.

In general, the range of NO_3-N lost can be quite large. Cookson et al. (2000) reported losses within the range of 32–100% of N applied. More recently, nitrate lost from agricultural land has been calculated to be within the range of 2 up to 100 kg N ha^{-1}year^{-1} (Libutti and Monteleone, 2017).

Potassium losses were mostly consistent with results reported by Alfaro et al. (2006), staying within a range of 1–49 kg ha^{-1}, except in fall 2019 where the cumulative K leached from both the weedy and weed-free plots exceeded 100 kg ha^{-1}. Values above 50 kg ha^{-1} were also recorded by Li et al. (2018) who found a strong positive correlation

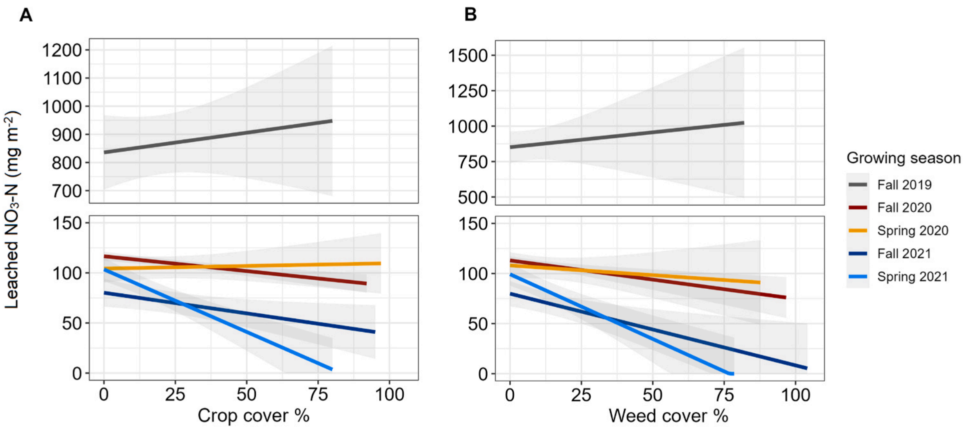

Fig. 2. Effect of crop cover (A) and weed cover (B) on amount of NO_3-N leached in groundwater throughout each growing season.

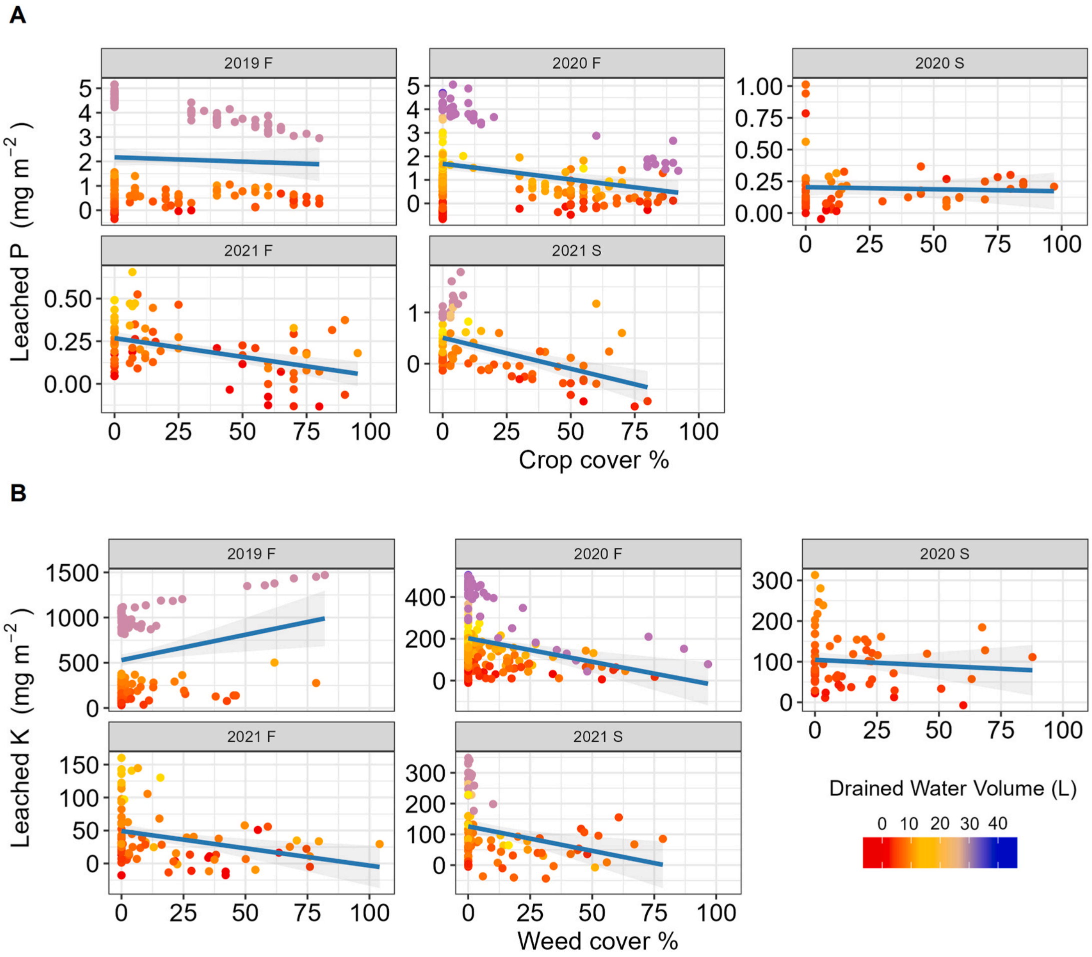

Fig. 3. (A) Effect of crop cover, percolated water volume and growing season on amount of P lost. (B) Effect of weed cover, percolated water volume and growing season on amount of K lost.

between irrigation and leachate volumes for P and K, in the same way they did for nitrates. There seems to be no environmental or health risks associated to excess K in groundwater, with limits set only by some European countries (Arienzo et al., 2009). Monitoring the loss of all elements, even the ones that are not considered hazardous, is important to gain a better understanding on how to increase the overall efficiency of fertilizer inputs. As mentioned by Lawniczak et al. (2016), N:P and N:K ratios in the soil can cause N leaching. The effect that these ratios have on nutrient losses is made even more complex by interactions with soil characteristics variable throughout the year, such as soil temperature and moisture (Cookson et al., 2000).

Phosphorus losses were influenced only by crop cover. The cumulative P leached in the fall/spring was within the 0.005–0.6 kg ha^{-1} range, which seems to be on the lower end compared to values found in other studies (Erickson et al., 2005; Fortune et al., 2005). Phosphorus uptake by both crop and weeds was also low (around 2–3 kg ha^{-1}). The pH of the soil used in this trial was around 8. Soil pH levels above 7.5 or below 6 increase soil P immobilization in the soil (do Nascimento et al., 2018). Dhaliwal et al. (2021) recorded P uptake by weeds at around 9 kg ha^{-1} in a rice cropping system, grown in a soil with 7.8 pH, while total P uptake by the crop was around 22 kg ha^{-1}. Cereals may have a higher capacity to mobilize phosphorus in high pH soils, but this remains to be clarified. If so, it would be worth investigating if weed communities dominated by grasses are correlated with higher P leaching compared to weed communities dominated by forbs. Some forbs are known to be hosts of Arbuscular Mycorrhizal Fungi (AMF) and could therefore support inoculation by AMF of the cabbage crop improving the P uptake capacity of cabbage and therefore reduce leaching (Nelson and Achar, 2001).

Considering the role of water in leaching dynamics, the role of agroecological practices such as no-till management could help reduce the variability of nutrient losses which derive from pedo-climatic conditions. Our trial focussed on the timing of weeding but other field management practices (e.g., mowing, tillage) should be considered to support the benefits of no-till systems in horticulture. Yagioka et al. (2015) conducted a trial in which weeds were mowed once a month and left as green mulch. Although they found a positive effect of weed cover in reducing NO_3-N losses in two other vegetable crops (pumpkin and eggplant), the no-till systems yielded less compared to the tilled systems at the same fertilizer dose despite leaving a 1 m inter-row. Constantin et al. (2010) mentioned that the effect of no-till practices on both leaching and production are dependent on soil and climate, which calls for an increase in studies on conservative agriculture in vegetable cropping systems.

Generally, in vegetable crops, the potential service provision delivered by weeds is also associated with a negative impact on crop yield and market value (Virili and Moonen, 2022). Results from this trial showed that the weed biomass which developed after the end of the critical weed-free period caused cabbage yield losses above the 5% and even 10% threshold in two out of the five cropping seasons. This confutes findings from Weaver (1984), who found that a 20 day weed-free period from crop transplanting was sufficient to achieve acceptable cabbage yields. In general, little is known on the interaction between collards and non-crop vegetation. Optimizing input management, fertilizers especially, has been found to select for more diverse and less competitive weed communities (Blackshaw and Brandt, 2008; Jiang et al., 2018;

Song et al., 2021). Thus, implementing several Integrated Weed Management (IWM) practices, coupled with lower input levels, would allow to accept higher weed densities.

5. Conclusions

Our findings support the hypothesis that increased vegetation cover provided by weeds can mitigate nitrate and potassium leaching. Different weed functional groups and diversity levels of weed communities should be tested to further understand this topic. A negative effect of weed cover on crop biomass was found in only two out of five growing seasons, although additional data is needed to better understand cabbage requirements in terms of critical weed control. Although lysimeters are useful to limit variability in soil conditions, they also pose limits. The number of available lysimeters is normally limited and does not allow to amplify the number of contrasting treatments. Future studies may benefit from adopting a field-level approach using ceramic suction cups, for example, to increase data points and allow to investigate more treatments at the same time, or to compare different soil types. However, the trial respected a detailed sampling regime which provided insight on leaching dynamics supported by biological evidence rather than statistical evidence only.

CRediT authorship contribution statement

Anna-Camilla Moonen: Writing – review & editing, Supervision, Conceptualization. **Alessandra Virili:** Writing – review & editing, Writing – original draft, Software, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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