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Nutrient losses due to tuber adhesion of harvesting multiple potato cultivars at different soil water contents

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ABSTRACT

Very few studies have investigated the effects of crop morphological characteristics on soil loss due to crop harvest (SLCH). The present study investigates the soil, nutrient (nitrogen, N, phosphorus, P, and potassium, K), and organic carbon losses during the harvest of different potato cultivars with different morphological characteristics. The experiment is conducted at different soil water contents (SWC) controlled by different irrigation schemes, with the last irrigation 5, 10, and 15 days before harvest. At harvest time (early fall), in addition to measuring tuber yield (which was harvested manually) and SLCH, disturbed and undisturbed soil samples were collected in the field to measure various soil physicochemical properties and soil nutrient contents exported from the field. On average, 0.79 ± 0.36 Mg ha^{-1} soil, 580 g ha^{-1} nitrogen, 3 g ha^{-1} extractable phosphorus, 350 g ha^{-1} potassium, and 4.2 Kg ha^{-1} organic carbon were lost from the experimental fields at each harvest. The SLCH of the farms with Fontane, Challenger, and Agria cultivars was 1.21 ± 0.03 Mg ha^{-1} $harvest^{-1}$, which was about three times higher than the SLCH of the farms with Innovator, Banba, Red Scarlet, Sifra, and Arinda cultivars with an average SLCH of 0.46 ± 0.06 Mg ha^{-1} $harvest^{-1}$. The highest SLCH (2.57 Mg ha^{-1}) occurred when SWC was highest compared to the other SWC values (i.e., 0.42 Mg ha^{-1}). For a given soil stickiness, tuber length and specific surface area (SSA) generally explained the variation in SLCH values, with elongated tubers having lower SSA resulting in lower SLCH values.

Keywords: Potato varieties, Nutrient loss, soil erosion, tuber crops, tuber morphology.

1. Introduction

While water, wind, and tillage erosion are usually considered the most important soil loss processes, Poesen et al., (2001) drew attention to another phenomenon, namely soil loss due to root crop harvesting (SLCH). Ruysschaert et al., (2004) noted that in relatively flat agricultural lands, where water and tillage erosion are minimal, the soil is mainly lost during the harvest of tuber crops. The SLCH also removes nutrients and organic matter that, along with the lost mineral soil, leads to increased fertilizer requirements and tillage costs (Poesen et al., 2001; Ruysschaert et al., 2004; 2006; 2008). While globally SLCH affects soil used to produce a wide range of crops including sugar beet (*Beta vulgaris*), cassava (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), chicory (*Cichorium intybus*), yams (*Dioscorea hirtiflora*), the focus here is on potatoes. This is because the global potato (*Solanum tuberosum* L.) production exceeds 374 M tonnes with a harvested area of more than 20 M ha (Devaux et al., 2014). According to Khorami and Moghaddam (2021), the annual production of potatoes in Iran is five million tons, which is the fourteenth place in the world in the production of this crop. Hamedan province is the greatest producer with a share of about 24% in the country's potato production, while Ardabil, Isfahan, East Azerbaijan, Kurdistan, and Zanjan provinces, which together produce 63% of the country's potatoes, rank second to sixth. In Iran, there are many potato varieties, but only a few varieties are grown and are important to farmers. Of the varieties studied in this research, Fontane and Agria are the most widely grown in Iran.

Several controlling factors lead to large variability in SLCH. Ruysschaert et al., (2004) classified the factors associated with SLCH into three categories: 1) soil-dependent factors such as soil texture and water content at harvest, 2) crop characteristics such as tuber shape, size, and roughness, and 3) agronomic characteristics such as crop type, plant density, crop yield, and harvesting methods. The soil-dependent factors can be sub-divided into intrinsic properties such as soil texture and calcium carbonate concentration, and dynamic properties such as soil water content (SWC), soil structure, and the nature and concentration of organic matter (Ruysschaert et al., 2004). Although limited data are available on SLCH, Soenens (1997) estimated it to fall between 0.4 and 16 tonnes per hectare with an average of 2 tonnes per hectare per potato harvest in Belgium. These results were confirmed by Biesmans (2002), who reported an average of 1.2 tonnes per hectare per crop from 1999 to 2001. Later Ruysschaert et al., (2006) showed SLCH due to potato harvesting in Belgium varies from 0.2 to 3.6 tonnes per hectare with the variability attributed to soil-dependent factors, particularly SWC. Similarly, Auerswald et al., (2006) in Germany showed that climatic and soil conditions are major determinants of SLCH with soil transfer from the field in rainy regions being much greater than in drier regions. Faraji et al., (2017) quantified the SLCH due to potato harvesting in 47 farms in Khuzestan province, southwestern Iran to an average of 6.2 tonnes per hectare. Using these results, they extrapolated the SLCH to account for the entire province and the country (Iran) to be 26.8 and 732 thousand tonnes per year, respectively. More recently, Thomaz and Bereze (2021) evaluated the effects of SWC at the time of harvest on SLCH showing that an increase from 16.6 to 25.7% gravimetric almost tripled the SLCH from the field.

Along with the removal of topsoil, harvesting tuber crops removes associated nutrients that are rarely returned to the soil and must be off-set by additional fertilizer applications. Yu et al., (2016) estimated the loss of available nitrogen (N) and extractable phosphorus (P) to be 0.11 to 0.21 kg per hectare per harvest (manual harvesting) being caused by a soil loss of 1.53 to 1.87 tonnes per hectare due to potato harvest, and 0.001 to 0.06 kg per hectare per harvest being caused by a soil loss of 0.67 to 0.96 ton per hectare due to sweet potato harvest. Mwango et al., (2013) determined the losses of organic carbon (OC), N, P, potassium (K), calcium (Ca), Magnesium (Mg), and sodium (Na) along with soil loss due to potato harvesting (manual harvesting) in two villages in Tanzania. The loss for each of two villages were OC (29 and 23), N (3 and 2), P (0.01 and 0.003), K (0.3 and 0.1), Ca (2 and 1), Mg (0.5 and 0.2), and Na (0.1 and 0.01) kg per hectare per harvest (Mwango et al., 2013).

Although Ruysschaert et al., (2004) have well-outlined the important morphological characteristics of the crop affecting the SLCH, their observations were particularly focused on sugar beet. Very few publications quantify crop morphological or phenotypic characteristics on SLCH and most do not focus on potato. Isabirye et al., (2007) showed that the smoother skin and less kinked morphology of sweet potato caused less soil adherence to crop and therefore results in less SLCH values. However, they did not consider factors relevant to potato such as tuber eye depth. Most recently, Thomaz and Bereze (2021) evaluated the effect of potato morphology on SLCH showing that elongated potatoes (with a SLCH value of 1.54 kg ton^{-1} $harvest^{-1}$) transferred 20 % more sediment from the field compared to spherical potatoes (with a SLCH value of 1.28 kg ton^{-1} $harvest^{-1}$). In addition to the general shape of the tubers from the single variety (Agata), they measured tuber volume, weight, number, and volume of concavities as well as tuber length in three different axes showing less effect on SLCH compared to the general shape of the tubers.

Different mechanisms are involved in SLCH. For example, mechanized harvesting may capture soil clods along with tubers (Thomaz and Bereze, 2021). Ruysschaert et al., (2007) give the example of SLCH from mechanically harvested potatoes in Belgium being greater than that of manually harvested potato in China. Ruysschaert et al., (2008) identify that SLCH peaked in the mid-twentieth century due to an increase in harvesting machinery but decreased sharply in recent decades due to the advancement of machinery. However, decreasing the capture of soil clods with machine harvesting does not prevent losses due to soil-tuber adhesion. In fact, there is a need to understand the role of soil-tuber adhesion linked to the crop's morphological or phenotypic characteristics as part of the SLCH process.

In this research, we aimed to examine soil and nutrient losses due to harvesting ten different cultivars of potato with documented morphological characteristics. We avoided the impact of harvesting clods not attached to tubers by harvesting manually. To understand the mechanisms controlling SLCH we proposed that potato characters such as those found by Thomaz and Bereze (2021), i.e., shape and size would be important but included other phenotypic features e.g., eye depth and skin smoothness. Along with the potatoes' morphology, we also examined the effect of SWC at the time of harvesting on soil and nutrient losses.

2. Materials and Methods

2.1. Experimental site

This research was conducted in 2017 in a research farm (37°22'27"N and 46°16'28"E) with an area of one hectare in Maragheh University, Maragheh, Iran. The average altitude of Maragheh City, located in the southwest of East Azerbaijan province, is 1450 meters above sea level. The climate class of Maragheh is temperate, cold, and semi-arid. The long-term (30-year) annual average rainfall in the city is about 302 mm (Rahmati et al., 2020). The maximum and minimum temperatures of the area are about 35 ^{0}C and -20 ^{0}C, respectively. During the potato growing season (Jun 2017 - Sep 2017), the maximum and minimum temperatures of the area were about 32 ^{0}C and 15 ^{0}C with around 1.5 mm of rainfall. Of the varieties investigated in this study, Fontane and Agria are the most grown in Iran and our region. The field was plowed to a depth of 30 cm in fall 2016 and to a depth of 10 cm in spring 2017. After that, the soil clods were crushed by disking being prepared for planting.

Table 1. Basic soil characteristics of experimental farm

Sand	Silt	Clay	Soil texture	OC	EC	pH	LL	PL	PI	AR
	%		-	%	dS m^{-1}	-		%		-
54.2	34.0	11.8	Sandy loam	0.6	2.07	7.57	32.84	28.46	4.38	0.37

OC: organic carbon, EC: electrical conductivity, LL: liquid limit, PL: Plastic limit, PI: Plasticity index, AR: Activity ratio

The basic characteristics of the soil from the experimental site with a depth of 30 cm are reported in Table 1. The experimental farm soil has a sandy loam texture, containing low clay content (11.8 %). The value of soil OC content of 0.63, a value of electrical conductivity (EC) equal to 2 dS m^{-1} and pH equal to 7.6 indicate the non-saline and neutral soil is suitable for potato cultivation, although it is poor in terms of OC content.

2.2. Potato planting, growing, and harvesting ~

We planted (Fig. 1a) the potatoes in early June 2017, falling into the routine planting time in the region (May 6 to June 6) due to the climate condition. Seed tubers were planted manually at a depth of 8-12 cm and one seed within an area of 40 × 60 cm^2. A lister was used to prepare the furrows and beds before planting and then tubers were planted in the middle height of the beds. The fertilizer requirements of the experimental site were determined based on the soil analysis before planting. Then, according to the fertilizer requirements, all plots were fertilized by broadcasting 200 kg ha^{-1} monoammonium phosphate (with 102 kg ha^{-1} P_2O_5 and 22 kg ha^{-1} N) and 150 kg ha^{-1} urea (with 69 kg ha^{-1} N) at the time of planting. The drip irrigation (Fig. 1b) was applied every three days in the same way for all plots (except the last irrigation, which is described in Section 2.5. Statistical Analysis). Harvesting was done manually (Fig. 1c) in early September 2017 so that for each treatment (subplot), side rows were removed to exclude marginal effects, and the rest of the tubers were transferred to the laboratory for necessary measurements. In this research, we used manual harvesting rather than mechanized harvesting because we were only interested in the soil adhered to the potatoes and not interested in harvested soil clods which usually occurs in mechanized harvesting.

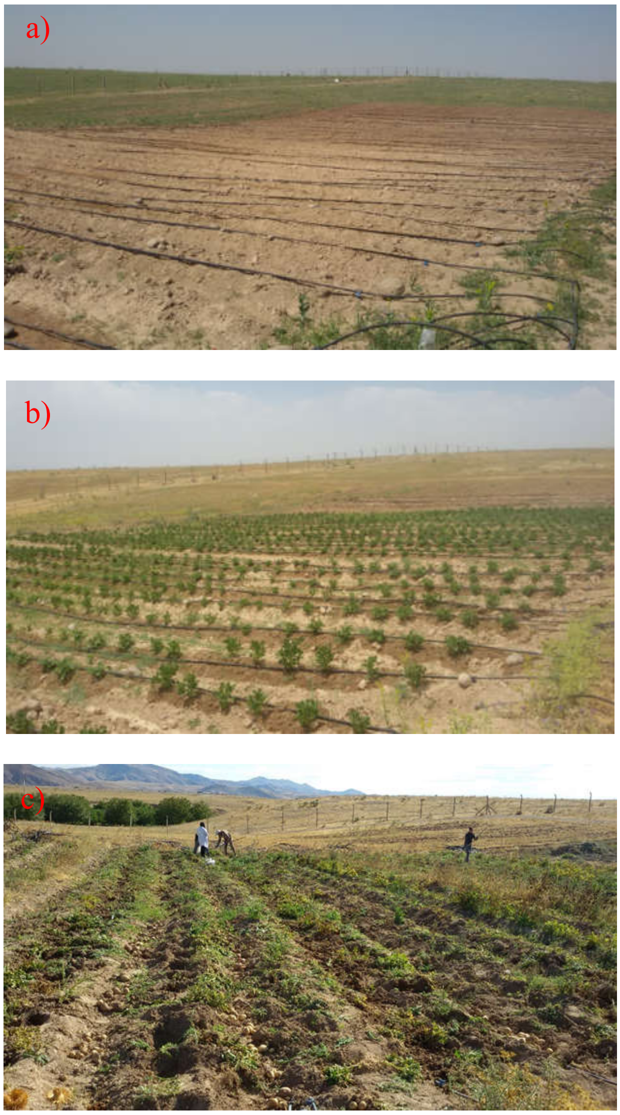

Fig. 1. Experimental field at planting (a), growing (b), and harvesting (c).

2.3. Soil sampling

At harvest, soil samples were taken from each subplot to examine the properties of the soil. Composite disturbed soil samples were taken from a depth of 0-30 cm to determine the basic characteristics of the soil including soil separates and texture class, OC, EC, pH, and Atterberg limits in experimental sites. Undisturbed samples (for bulk density) were taken using sampling cylinders with a diameter of 5.5 cm and a height of 4 cm from a depth of 5-10 cm. Both disturbed and undisturbed samples were taken separately from both furrow and hill to investigate the effect of different conditions inside the furrows and trenches on soil and nutrient losses due to potato harvesting.

2.4. Laboratory measurements

2.4.1. SLCH quantification

Both mass-specific ($SLCH_{spec}$) and area-specific ($SLCH_{crop}$) soil loss expressions (Ruysschaert et al., 2004) were used to quantify soil removal from each subplot due to potato harvesting. In the case of $SLCH_{spec}$, the soil loss was calculated per unit weight of harvested crop:

$$SLCH_{spec}\left(kg\ kg^{-1}\right) = \frac{M_{ds} + M_{rf}}{M_{crop}} \quad [1]$$

where, M_{ds}, M_{rf}, and M_{crop} (all in kg) represent the mass of dry soil leaving the field (soil adhering to tubers), the mass of rock fragments, and the net mass of the crop, respectively. The mass of loose soil adhering to the tubers was determined by grinding, washing, and drying it in the oven and separating the rock fragments. The $SLCH_{crop}$ is calculated as below:

$$SLCH_{crop}\left(kg\ ha^{-1}\ harvest^{-1}\right) = SLCH_{spec} \times M_{cy} \quad [2]$$

where M_{cy} (kg ha^{-1} per harvest) is the net crop yield.

2.4.2. Nutrient loss quantification

To estimate the amount of nutrients (N, extractable P, and K) and OC removed from each subplot, the amount of the above elements were measured per unit mass of soil samples and then multiplied by the mass of loose soil (excluding rock fragments) lost from each subplot to obtain the total amount of nutrients removed from each field. Hereafter for convenience, the loss of N, extractable P, extractable K, and OC due to crop harvesting will be termed NLCH, PLCH, KLCH, and CLCH, respectively.

2.4.3. Measurement of yield and morphological characteristics of tubers

To determine crop yield, we calculated the number of plants per hectare (N_{crop}) using Eq. 3, and then crop yield (Y) per hectare was obtained from Eq. 4:

$$N_{crop}\left(ha^{-1}\right) = \frac{10000}{0.6 \times 0.4} \quad [3]$$

$$Y\left(kg\ ha^{-1}\right) = N_{crop} \times M_{tuber} \quad [4]$$

where M_{tuber} is the average tuber weight per plant in each subplot being measured within experimental subplots.

To evaluate the effect of morphological characteristics of potato on soil and nutrient losses, the dimensions of all tubers (length, width, and height) were recorded using a caliper and then the mean for each subplot was reported. The volume of potato tubers was measured by water displacement.

To calculate the specific surface area (SSA) of the tubers, we assumed a spherical geometry for them and then computed their SSA according to formulations suggested for spherical sand particles in soil physics (Lal & Shukla, 2004). To do this, the average equivalent diameter of the tubers was calculated using equation (5) for the enclosed volume of a sphere:

$$D_e = \sqrt[3]{\frac{6 \times V}{\pi}} \quad [5]$$

where V is the average volume of tubers measured in the laboratory and D_e is the mean equivalent diameter of the tubers. By calculating the equivalent spherical diameter of tubers, the SSA of equivalent spherical tubers was calculated from the following equation, which is initially introduced to calculate the specific surface area of spherical sand particles in soil physics (Lal and Shukla, 2004):

$$SSA = \frac{\pi D_e^2}{M} \quad [6]$$

Where, SSA is the specific surface area of equivalent spherical tubers ($cm^2\ g^{-1}$), D_e is the mean equivalent diameter of the tubers (cm) and M is the average mass of single tubers (g).

2.4.5. Measurement of soil properties

Soil texture was measured according to hydrometric method (Gee and Or, 2002), bulk density was measured through undisturbed samples using sampling cylinders with 5.6 cm diameter and 4.2 cm high according to Grossman and Reinsch (2002), water content was measured using gravimetric method at a depth of 0-30 cm at the time of harvest, and EC of the soil samples was measured in the saturated paste extract using an EC-meter. Atterberg limits including liquid (LL) and plastic (PL) limits were measured according to McBride (2002) from which we determined the plasticity index (PI = LL – PL) as well as activity ratio (AR = PI/clay). Soil OC was also measured using the wet oxidation method according to Nelson and Sommers (1996), extractable P according to Olsen (1954), and K according to the ammonium acetate method (Knudsen et al., 1982). The N content in soil samples was estimated according to Rashidi and Seilsepour (2009):

$$N(\%) = 0.026 + 0.067OC \quad [7]$$

2.5. Statistical analysis

A split plot experiment with a randomized complete block design (RCBD) with three replications was conducted to address the research questions. Different SWC at harvest was considered as the main factor (first) and the potato varieties as the second factor. Solanum tubers of ten potato cultivars (Solanum tuberosum L.)

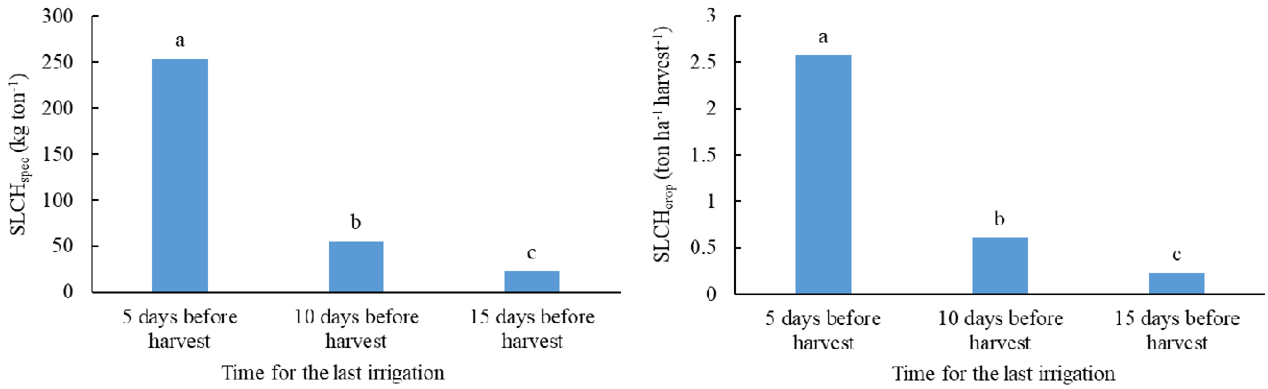

Fig. 2. The mass-specific SLCH$_{spec}$ (left) and area-specific SLCH$_{crop}$ (right) soil loss from fields at different soil water content at harvest.

including Challenger, Sante, Innovator, Banba, Red Scarlett, Sifra, Picasso, Agria, Fontane, and Arinda were cultivated in Maragheh University experimental field (Table 2). By choosing these varieties, we intended to have crops with different sizes, shapes, and skin smoothness of tubers as well as different depths of tuber eye.

Each main plot was divided into 10 subplots (with an approximate area of 2.5 × 2.5 square meters) where the potato varieties were randomly planted inside each subplot. To account for different SWC at harvest time, the last irrigation of the plants in plots 1 to 3 was done 5, 10, and 15 days before harvest, respectively, where hereafter we call them I_5, I_{10}, and I_{15}. In our region, farmers usually irrigate for the last time 7 to 10 days before harvest. Therefore, in this study, we used 5 days (shorter than the local norm) and 15 days (longer than the local norm) in addition to the usual local value of 10 days to better capture the impact of soil wetness on crop harvesting-related soil loss.

To examine the controlling factors on soil lost by potato harvesting, we performed a principal component analysis (PCA) and generated biplots to show both the observations and the original variables in the principal component space (Gabriel, 1971). Variables used in this analysis include SWC, bulk density (D_b), tuber shape index (SI), tuber dimensions (L: length, H: height, W: width, and D_e: equivalent diameter), specific area (As), volume (V) and mass (M) as well as SLCH$_{spec}$ and SLCH$_{crop}$.

3. Results and Discussion

3.1. SLCH under different potato varieties and water contents at harvest

The analysis of variance showed that both SLCH$_{crop}$ and SLCH$_{spec}$ differed ($p < 0.01$) among different irrigation schemes resulting in different SWC at harvest. A difference ($p < 0.05$) was also observed among potato varieties in term of SLCH$_{crop}$, while no significant difference was observed among them in terms of SLCH$_{spec}$. The interaction effect of potato varieties and irrigation schemes was also insignificant.

The average SLCH$_{crop}$ and SLCH$_{spec}$ at different irrigation schemes is shown in Fig. 2. According to the results, for both SLCH$_{crop}$ and SLCH$_{spec}$, the greatest soil loss occurred in the first irrigation scheme (I_5: irrigated 5 days before harvest), and the least soil loss occurred in the third irrigation scheme (I_{15}: irrigated 15 days before harvest). The I_5 with SLCH$_{crop}$ equal to 2.6 tonnes ha^{-1} harvest^{-1} and with SLCH$_{spec}$ equal to 254 kg tonnes^{-1} of harvested tubers, which was 10 times greater compared to I_{15} with SLCH$_{crop}$ equal to 0.23 tonnes ha^{-1} harvest^{-1} and SLCH$_{spec}$ equal to 22 kg tonne^{-1} of harvested tubers. The applied irrigation schemes of I_5, I_{10}, and I_{15} resulted in 11.05, 5.85, and 4.68 g/100g water contents at harvest time, respectively. The increased SWC enhanced the adhesion of soil particles to the tubers and causes greater soil loss. The effect of SWC on SLCH can be more pronounced in our experimental site with a lower percentage of clay content (12%) and a lower amount of organic carbon (0.4%), as key controllers of SLCH. This happens because, in such soils the adhesion between soil particles and tubers is mainly controlled by SWC. These results are consistent with those of Ruysschaert et al., (2007) in Belgium, Duval (1988) in France, and Yu et al., (2016) in China showing similarly that the increased SWC at harvest time causes more soil loss due to increased soil adhesion to tubers.

All irrigation schedules resulted in SWC (5 to 11 g/100g) well below the PL of the soils studied (28.5 ± 0.8 g/100g). Therefore, it seems that even in drier soil, a small change in SWC results in considerable change in SLCH. On the other hand, assuming that the optimum SWC for workability is 0.9 × PL (Obour et al., 2017; Kouselou et al., 2018), one might expect the lowest adherence of soils to tubers when the SWC is close the 0.9 × PL, at least in sandy loam soil examined in this experiment. However, the measured SLCH when the soil was drier than 0.9 × PL opposes this showing less soil

Table 2. Basic characteristics of planted potato varieties[¥]

Variety	Release	Breeder country	Parent	Parent 2	Tuber size	Tuber shape	Tuber eye depth	Skin smoothness	Comment
Challenger	2008	Netherlands	Aziza	Victoria	medium	oval	shallow	medium	early maincrop
Sante	1983	UK	Y 66-13-636	AM 66-42	large	short oval	shallow to medium	smooth	maincrop
Banba	2000	Ireland	Slaney	Estima	large	oval long	shallow	medium	early maincrop
Red Scarlett	2004	Netherlands	ZPC 80 O239	MANS.MGB78-286	medium	oval long	shallow	intermediate to rough	early
Sifra	2008	Netherlands	Mondial	Robinta	large	oval round	medium	medium	late maincrop
Picasso	1994	UK	Cara	Ausonia	large to very large	oval	shallow to medium	medium	maincrop
Agria	1985	UK	Quarta	Semlo	large	oval long	very shallow to shallow	medium	maincrop
Fontane	1999	UK	Agria	AR 76-34-3	large	oval	shallow to medium	medium	early maincrop
Arinda	1993	Netherlands	Vulkano	AR 74-78-1	large to very large	oval long	very shallow to shallow	intermediate to rough	early maincrop
Innovator	1999	Netherlands	Shepody	RZ 84-2580	large to very large	oval long	shallow	rough	second early

¥) Sources: Potato varieties database at https://varieties.ahdb.org.uk/varieties; The European Cultivated Potatoes at https://www.europotato.org/; World Class Seed Potatoes at https://www.hzpc.com/; Canadian Food Inspection Agency at https://inspection.canada.ca/eng/1297964599443/1297965645317; IPM Potato Group Limited at https://ipmpotato.com/; Garden design experts at https://garden-en.desigusxpro.com/; and Agrico at https://www.agrico.nl/; https://www.potatopro.com/potato-varieties/.

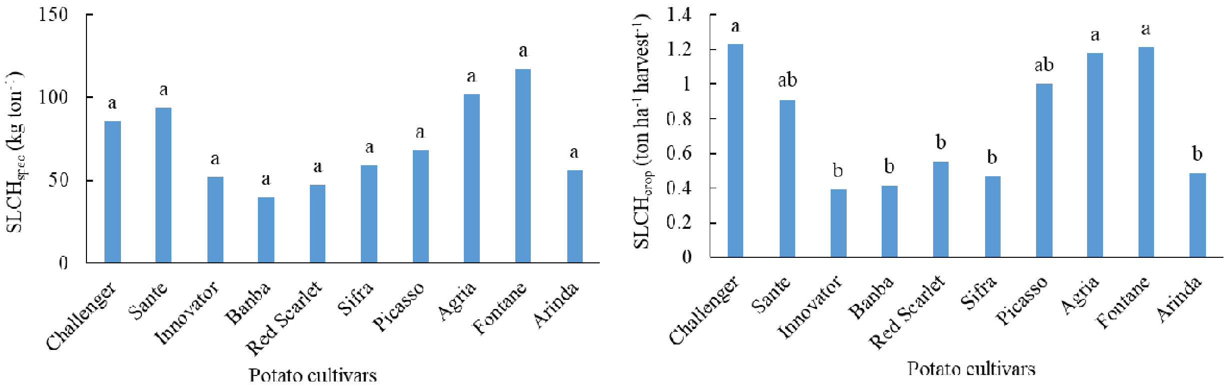

Fig. 3. The mass-specific $SLCH_{spec}$ (left) and area-specific $SLCH_{crop}$ (right) soil loss from fields under different potato varieties.

loss when the SWC is less. Several researchers (Sumithra et al., 2013; Faraji et al., 2017; Kuhwald et al., 2022, among others) have already mentioned that SWC and texture are the most important factors determining the SLCH, but these studies did not present Atterberg limit data. However, it seems that soil mechanical properties such as coherence and adherence which are described by the Atterberg limits play a role in determining SLCH. As Atterberg limits are positively correlated with clay and organic matter percentage, future research on SLCH should include Atterberg limit data to allow direct comparison between studies. Then, optimal conditions to minimize SLCH can be expressed in terms of soil behavior.

Innovator, Banba, Red Scarlett, Sifra, and Arinda had the least soil loss in terms of $SLCH_{spec}$ (not significantly) and $SLCH_{crop}$ ($p < 0.05$), and Fontane, Challenger and Agria had the greatest $SLCH_{spec}$ (not significantly) and $SLCH_{crop}$ ($p < 0.05$) while soil loss was intermediate in other varieties (Fig. 3). Since there were no significant differences for $SLCH_{spec}$, only $SLCH_{crop}$ is discussed below. The $SLCH_{crop}$ in Fontane, Challenger and Agria varieties was 1.21 ± 0.03 Mg ha^{-1} harvest^{-1}, which is about three times that of Innovator, Banba, Red Scarlett, Sifra, and Arinda varieties with a $SLCH_{crop}$ of about 0.46 ± 0.06 Mg ha^{-1} harvest^{-1}. The higher $SLCH_{crop}$ in Challenger and Agria varieties can be subjected to their smaller dimensions (with an average tuber volume of 43 ± 0.09 cm^3), which is also confirmed by measurement of morphological characteristics. However, the high $SLCH_{crop}$ in Fontana varieties needs to be explored more since its shows similar morphology compared to other varieties with lower $SLCH_{crop}$. The possible reasons for the high $SLCH_{crop}$ in Fontana varieties might be related to its different structure tuber skin causing more adhesion of soil particles to tubers, which needs to be investigated in future research. While higher yields for Challenger and Agria might be the determinant of higher $SLCH_{crop}$ values; this is not the case for Fontane. Studies linking different potato varieties and their morphologies to mass-specific or area-specific soil loss are lacking. The only relevant study is Thomaz and Bereze (2021) who examined the effect of potato morphology (shape, weight, and volume of the tubers, number, and volume of concavities, as well as tuber dimensions) on SLCH for a single species. Their results showed that elongated potatoes resulted in 20 % more loss of soil from the field compared to spherical potatoes. Oshunsanya et al., (2019) also showed that root hair density and root cortex along with clay and organic matter significantly contributed to $SLCH_{spec}$ variation.

3.2. Nutrient loss along with SLCH

There were differences in losses of nitrogen (NLCH), extractable phosphorus (PLCH), extractable potassium (KLCH), and organic carbon (CLCH) among potato varieties ($p < 0.05$) and irrigation schemes ($p < 0.01$). The interaction effect of potato varieties and irrigation treatments on the above parameters was not significant. This simply means that the effect of potato varieties on nutrient and OC loss does not depend on the value of irrigation measures. This could be plausible if we know that potato varieties cause soil losses and consequently nutrient losses due to their morphological characteristics, which are mainly controlled by their genetics and not by irrigation systems, regardless of soil particles and soil wetness status. In all cases losses were greatest under I_5 and least under I_{15} (Fig. 4). The losses of N, P, and K were calculated based on their routine fertilizers and I_5 caused the loss of about 2 kg equivalent potassium sulphate, 30 g equivalent triple superphosphate, and 2.8 kg equivalent urea per hectare. The nutrient losses obtained in this study are in the range obtained from the loss of these nutrients in a study conducted in northern China (Yu et al., 2016). The loss of nutrients may be small compared with fertilizer application, but their fate as contaminants in the water cycle and surface and ground water might be cause for concern.

The comparisons of the average nutrient loss under different potato varieties are shown in Fig. 5, which the

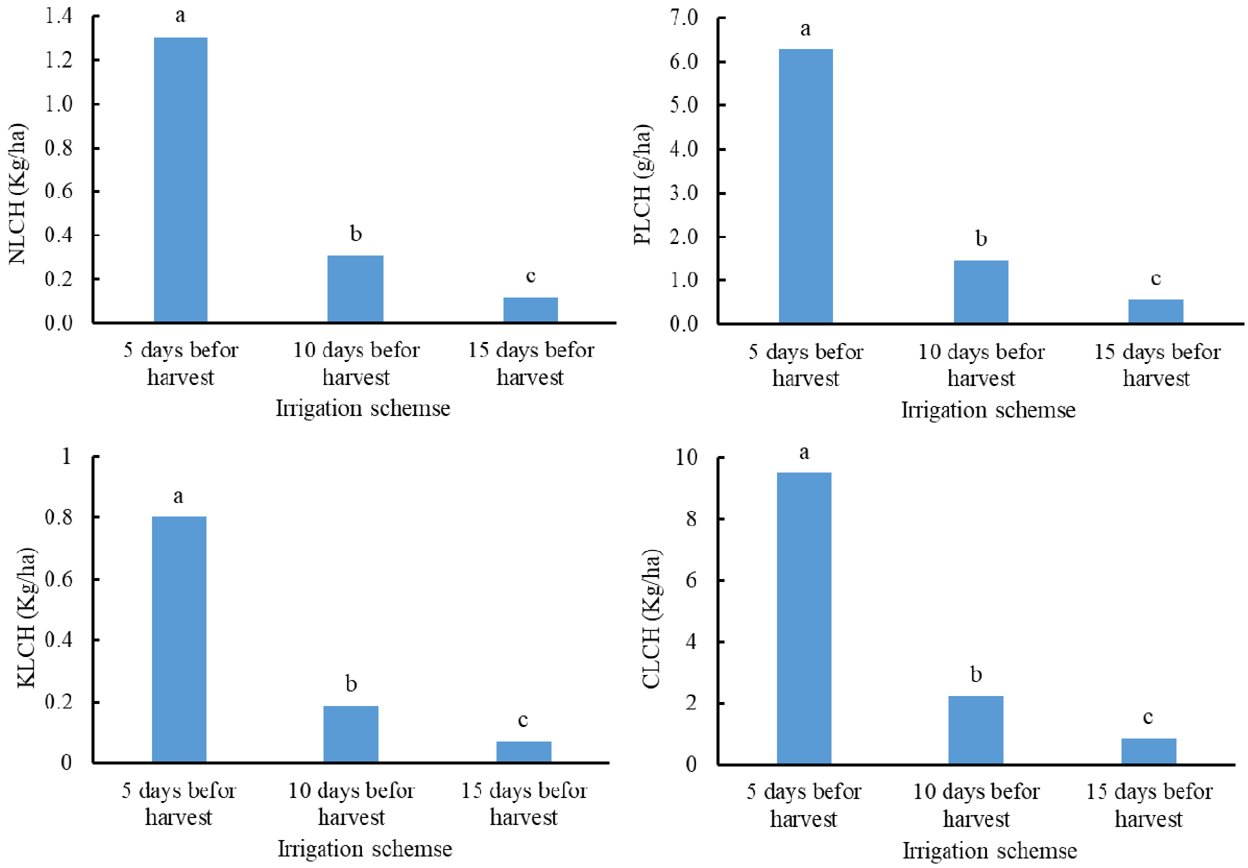

Fig. 4. The nitrogen (NLCH), extractable phosphorus (PLCH), potassium (KLCH), and organic carbon (CLCH) losses from the fields at different soil water contents at harvest.

results were in line with soil loss rates where Innovator, Banba, Red Scarlett, Sifra, and Arinda had the lowest nutrient loss and Fontane and Challenger had the highest nutrient loss per hectare and nutrient loss in other varieties was intermediate.

3.3. Factors affecting SLCH

To evaluate which variables, soil characteristics (SWC and D_b) and/or crop characteristics (tuber shape, dimensions, volume, specific area, and yield), are correlated with SLCH, a PCA analysis is conducted, with the results presented in biplots (Fig. 6). In a biplot, closely aligned variables are positively correlated while opposite direction aligned arrows are negatively correlated with each other. In both cases, the magnitude of the arrows implies a stronger correlation among those variables. There is no correlation between variables aligned with 90 degrees to each other (Rahmati et al., 2018). Fig. 6-a, with data from all irrigation schemes included in the PCA analysis, shows both $SLCH_{spec}$ and $SLCH_{crop}$ are mainly controlled by SWC (correlation coefficients 0.599 and 0.536 respectively) and to lesser extent by soil bulk density (correlation coefficients -0.293 and -0.278 respectively). Thus, within the ranges tested wetter soil and lower bulk density result in greater soil loss from potato harvesting. Because the higher the SWC, the more the soil particles adhere to the tubers. On the other hand, the lower bulk density of the soil means that the soils are powdered and have less cohesion and probably more adhesive forces (especially when the soil is wet). Therefore, one could expect more soil particles to adhere to potato tubers when the soil is less cloddy and less compacted. The remaining factors (mainly crop characteristics) are less correlated with SLCH showing much weaker correlation coefficients. Several researchers (Auerswald et al., 2006; Ruysschaert et al., 2006; Jurisic et al., 2011; Mwango et al., 2013) have already shown that SWC at harvest is one of the strongest determinants of SLCH.

To investigate the extent to which plant morphological factors may be relevant to SLCH when soil moisture status is similar, we did PCA analysis separately for each of the three water contents (Fig. 6-b, c, and d). The results show that the importance of tuber morphological characteristics for SLCH depend on soil moisture. When the SWC at harvest was high (Fig. 6-b),

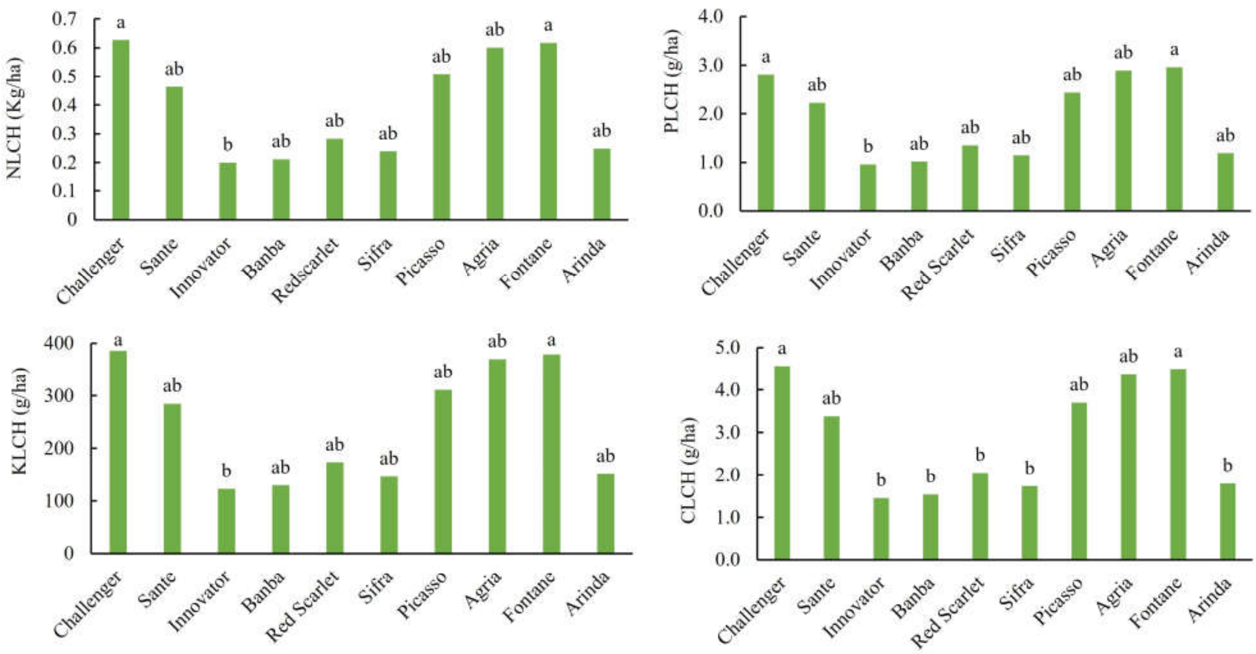

Fig. 5. The nitrogen (NLCH), extractable phosphorus (PLCH), potassium (KLCH), and organic carbon (CLCH) losses from the fields under different potato varieties.

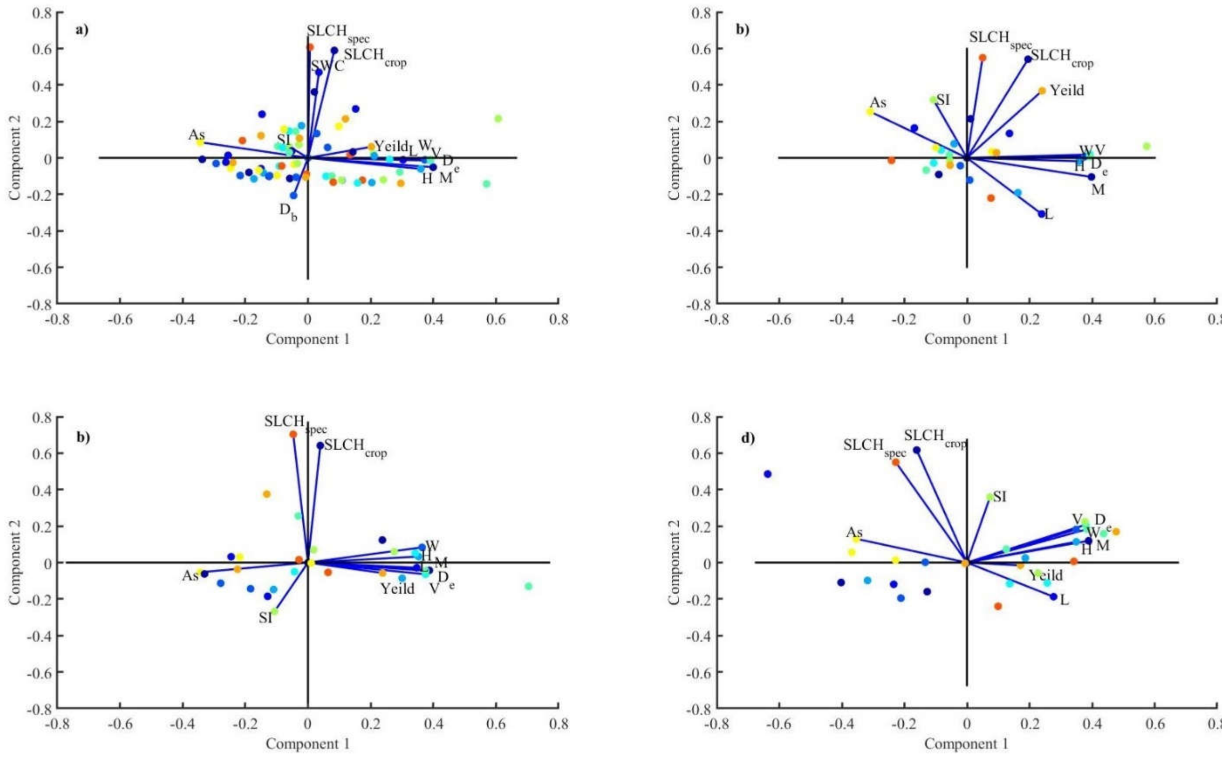

Fig. 6. The relationship between soil water content (SWC), bulk density (D_b), tuber shape index (SI), dimensions (L: length, H: height, W: width, and D_e: equivalent diameter), specific area (As), volume (V) and mass (M) as well as yield and mass- ($SLCH_{spec}$) and crop ($SLCH_{crop}$) -specific soil loss due to potato harvesting under four different conditions when data from a) all irrigation schemes, b) first irrigation scheme, c) second irrigation scheme, and d) third irrigation scheme are included.

the SLCH is mainly explained by yield rather than morphological characteristics of tubers i.e., the greater the yield, the greater the SLCH. This simply means that in wet soil SLCH is mainly determined by the number of tubers harvested independent of the tuber shape or dimensions. However, in drier soil, some morphological characteristics of tubers become important for SLCH (Fig. 6 c-d). Due to the drier condition of the soil in this experiment (Fig. 6-d) and the non-dominant effect of SWC, it seems that the length of tubers starts to show dominant effects on SLCH whereas the longer the length of the tubers, the lower the SLCH is. This outcome opposes those obtained by Thomaz and Bereze (2021) who showed that elongated potatoes transform 20 % more sediment from the field compared to spherical potatoes. It seems that our obtained results are more logical compared to those of Thomaz and Bereze (2021) because smaller tubers might have a higher SSA and more possibility to adhere to soil particles compared to elongated ones. This is also confirmed by the SSA of tubers in our experiments. The SSA of tubers shows a positive correlation with SLCH (Fig. 6-d). This means that the higher the SSA (probably due to smaller tubers), the higher the amount of lost soil is. Finally, as seen from Fig. 6-c, when the soil wetness is intermediate, the effects of nearly all morphological characteristics of tubers on SLCH are negligible. The obtained results simply show that if one attends to examine the effects of morphological characteristics on SLCH, it is very important to make sure that the effects of morphological characteristics are not diminished by another stronger controller such as SWC.

4. Summary and Outlook

In this study, soil (SLCH) and nutrient (nitrogen, NLCH; extractable phosphorus, PLCH; potassium, KLCH; and organic carbon, CLCH) losses were investigated during the harvest of 10 different potato varieties at three different SWC at harvest. Our findings suggest that:

- The last irrigation 5 days before harvest resulted in 10 times higher soil loss in the studied farm than the last irrigation 15 days before harvest (2.6 vs. 0.23 Mg ha^{-1} harvest^{-1}).
- Cultivation of Fontane, Challenger, and Agria varieties of potato resulted in 3-times greater soil loss from examined farm compared to that of Innovator, Banba, Red Scarlett, Sifra, and Arinda varieties (1.2 vs. 0.46 Mg ha^{-1} harvest^{-1}).
- Applying the last irrigation 5 days before harvest resulted in 6 to 10-times higher nutrient loss from examined farm compared to when the last irrigation was 15 days before harvest (with N, P, K, and OC losses of 1300, 6.2, 800, and 9500 g ha^{-1} harvest^{-1} vs. 150, 1, 100, and 860 g ha^{-1} harvest^{-1}, respectively).
- The SWC at harvest time was positively correlated with soil loss from experimental plots showing a correlation coefficient greater than 0.5.
- Attending to evaluate the effects of morphological characteristics of tubers on SLCH, it is important to omit the effects of other stronger characteristics including SWC, bulk densities, and probably soil texture.
- When soil stickiness was high due to higher water content, yield was the only factor explaining the variation in SLCH. However, when the stickiness of soil was low due to lower water content, the length and specific surface area of the tubers were negatively and positively, respectively, correlated with SCLH.

Considering that an increase in gravimetric SWC from about 5% to about 11% increased soil loss from 0.42 Mg ha^{-1} to about 2.6 Mg ha^{-1}, the potato industry in region isrecommended to reduce soil losses by optimal regulation of SWC at harvest. This will not only reduce the soil loss from fields, but also the probable contamination of surface and subsurface waters. Challenger and Picasso varieties had greater yields than other varieties. However, the amount of soil loss in these varieties was greater than other varieties.

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