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Productivity, quality, and nutrient uptake of intensive forage crop rotations based on corn in sandy soil (northern Morocco)

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ABSTRACT

Intensive dairy farming systems in the sandy soil of northwestern Morocco are based on three successive forage crops per year, including corn. The aim was to evaluate the productivity and the quality of different intensive crop successions based on corn in sandy soil. Three forage crops per year (winter, spring, and summer cropping seasons) were tested according to six successions: 1. fallow-corn-corn, 2. oat-corn-corn, 3. berseem-corn-corn, 4. pea/triticale-corn-corn, 5. oat-soybean-corn, and 6. berseem-corn-soybean. Each succession of crops was evaluated in two years field experiment using a randomized complete block design. Results revealed that oat-corn-corn and pea/triticale-corn-corn successions produced the highest dry biomass (46.5 t ha^{-1} $year^{-1}$). The crop succession of berseem-corn-soybean resulted in the lowest biomass (30.8 t ha^{-1} $year^{-1}$). The highest net energy for lactation was recorded at oat-corn-corn and pea/triticale-corn-corn successions (303 10^3 MJ ha^{-1} $year^{-1}$). The crop successions based on one corn (oat-soybean-corn and berseem-corn-soybean) recorded the lowest net energy for lactation (195.5 10^3 MJ ha^{-1} $year^{-1}$). The oat-corn-corn, pea/triticale-corn-corn, and oat-soybean-corn successions recorded the highest crude protein values (3.9 t ha^{-1} $year^{-1}$). Soil organic matter and the content of soil on total N, P, and Mg were similar for the different crop successions at the end of the experimental years.

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1. INTRODUCTION

Large dairy farms produce silage corn twice a year (spring and summer cropping seasons) in the sandy soil of northern Morocco. The advantages of forage corn are related to its high silage yield and energy value (Khan et al., 2015). Some producers intensify the rotations by introducing a third forage crop during the winter season, particularly legumes. The inclusion of legume forages in such intensive systems led to higher production of total crude protein (Deng et al., 2020). Two successive forage crops per year (corn, forage rape) produced 37 tons of dry matter with a high nutritive value (Wang et al., 2023). However, such intensive forage production may impoverish the sandy soil (Chauhan et al., 2012).

Sustainable corn production requires an adequate crop rotation (Chen et al., 2018; Chen et al., 2016). The negative impacts of corn monoculture have been reported by many authors (Behnke et al., 2020; Mera et al., 2021). The monoculture of sorghum and corn resulted in soil nutrient depletion over the production seasons (Perera & Weerasinghe, 2014). Furthermore, the monoculture of corn has high fertilizer requirements compared to a rotation of corn and legumes (Behnke et al., 2020; N'Dayegamiye et al., 2015). Many authors reported a significant enhancement of corn yield with corn-legumes rotation (Huynh et al., 2019; Riedell & Osborne, 2017; Uzoh et al., 2019). Corn-legume rotation enhanced yield by 5.4% (Yuan et al., 2022) compared to continuous corn production (Huynh et al., 2019; Uzoh et al., 2019). In fact, the inclusion of legumes in the rotations of rice-wheat and maize-wheat resulted in an improvement of soil organic carbon, available nitrogen (N), and phosphorus (P) (Ghosh et al., 2020).

In the southern Mediterranean area, less attention has been given to evaluate the efficacy of a forage cropping rotation based on a succession of corn and other forage crops during a year in assuring self-sufficient biomass production for large dairy farms compared to a mono-cropping of corn. Furthermore, no results of the impact of an intensive forage system based on two successive corn production on soil fertility have been reported. The aim of the study was to evaluate the productivity, the quality, and the nutrients uptake of different intensive forage crop rotations based on corn in sandy soil (northern Morocco). Additionally, this study will help determine the impact of intensive forage systems on soil fertility.

2. MATERIALS AND METHODS

2.1 Experimental site and studied soil

Field experiments were conducted during the 2018-2019 and 2019-2020 seasons. The experimental site was located in the Loukkos area (Northern Morocco, 35°01'N, 6°21'W, 30 m from the sea level). The soil was sandy (86.4% sand). It contains 0.98% of organic matter and a total N of 0.06%. The other soil properties are reported in Table 1.

Table 1. Soil properties (0-30 cm)

Soil properties	Value
Sand (%)	87.4
Silt (%)	5.6
Clay (%)	7.7
pH[a]	7.7
Cation exchangeable capacity (meq 100 g^{-1})[b]	8.30
Electrical conductivity (ds m^{-1})[a]	0.14
Organic matter (%)[c]	0.98
Total nitrogen (%)[d]	0.06
Phosphorus (mg kg^{-1})[e]	86.5
Potassium (mg kg^{-1})[f]	199
Magnesium (mg kg^{-1})[f]	104
Copper (mg kg^{-1})[g]	1.19
Manganese (mg kg^{-1})[g]	7.9
Iron (mg kg^{-1})[g]	11.6
Zinc (mg kg^{-1})[g]	4.9

Remarks: [a] Determined in a soil: water ratio of 1/5;
[b] Determined using Cobaltihexamine Chloride method;
[c] Determined using Walkey-Black method;
[d] Kjeldahl extraction method;
[e] Olsen extraction method;
[f] Ammonium acetate extraction at pH = 7;
[g] DTPA extraction at pH = 7.3.

2.2 Forage crop successions and experimental design

Six forage crops: corn (*Zea mays* L., cv. P0725), soybean (*Glycine max* L., cv. Wendy Pzo), oat (*Avena sativa* L., cv. Panache), berseem (*Trifolium alexandrinum* L., cv. Akenaton), and an association of pea (*Pisum sativum* L., cv. Navarro) and triticale (x *Triticosecale* wittm., cv. Spectro) were tested in different crop rotations. Six crop rotations were evaluated: 1-fallow-corn-corn, 2-oat-corn-corn, 3-berseem-corn-corn, 4-pea/triticale-corn-corn, 5-oat-soybean-corn, and 6-berseem-corn-soybean. For each rotation, the first crop was sown in November and harvested in March. The second crop occupied the soil from March to July, and the third crop occupied the soil from July to November. All rotations were evaluated in a randomized complete block experimental design with five replications. The experimental plot size was 44 m^2 (8 m × 5.5 m). Each rotation occupied an experimental plot during two consecutive growing seasons (2018-2019 and 2019-2020).

2.3 Crop management

2.3.1 Winter crops: oat, berseem, and association of pea/triticale

The land was prepared by the cultivator before sowing the first crop of each rotation (winter cropping season). The sowing rates were 75 kg ha^{-1} and 30 kg ha^{-1} for oat and berseem, respectively. For the pea/triticale association, the sowing rate was 72 kg ha^{-1} for pea and 48 kg ha^{-1} for triticale. These crops were grown under rainfed conditions. For the first winter cropping season (November 2018 to March 2019), the rainfall was 153 mm. The average minimum and maximum temperatures were approximately 6.6 °C and 18.3 °C, respectively. For the second winter growing season (November 2019 to March 2020), the rainfall was 118 mm (Fig. 1). The average minimum and maximum temperatures were 8.0 °C and 18.8 °C, respectively.

Fertilization rates were based on the standards of forage crops fertilization applied by the farmers of the studied area. Oat and association of pea/triticale received 104 kg ha^{-1} of N, 26 kg ha^{-1} of P, and 91 kg ha^{-1} of K. For berseem, the soil was supplied with 30 kg ha^{-1} of N, 26 kg ha^{-1} of P, and 41 kg ha^{-1} of K. Ammonitrate, potassium chloride, and bulk fertilizer (10-30-10) were used as sources of nutrients.

2.3.2 Spring and summer crops: corn and soybean

After the harvest of the winter crop, the land was prepared by the cultivator. Then, the spring and summer crops (corn and soybean) were sown. The sowing rates were 120,000 kernels ha^{-1} for corn and 606,000 kernels ha^{-1} for soybean. A sowing pattern of 60 cm between twin lines of 40 cm spacing was performed for both crops. The seeds of soybean were inoculated with *Rhizobium japonicum*. The inoculation rate of 400 g ha^{-1} was applied to have around 10^6 bacteria per seed (Hungria et al., 2017).

For the spring growing season (April to July), the rainfall was 120 mm for 2019 and 76 mm for 2020 (Fig. 1). For the summer growing season (August to November), the rainfall was 76 mm for 2019 and 83 mm for 2020. The average minimum and maximum temperatures were around 14.7 °C and 24.8 °C during the spring and summer seasons, respectively. The temperature evolution during the cropping seasons was reported in Figure 1.

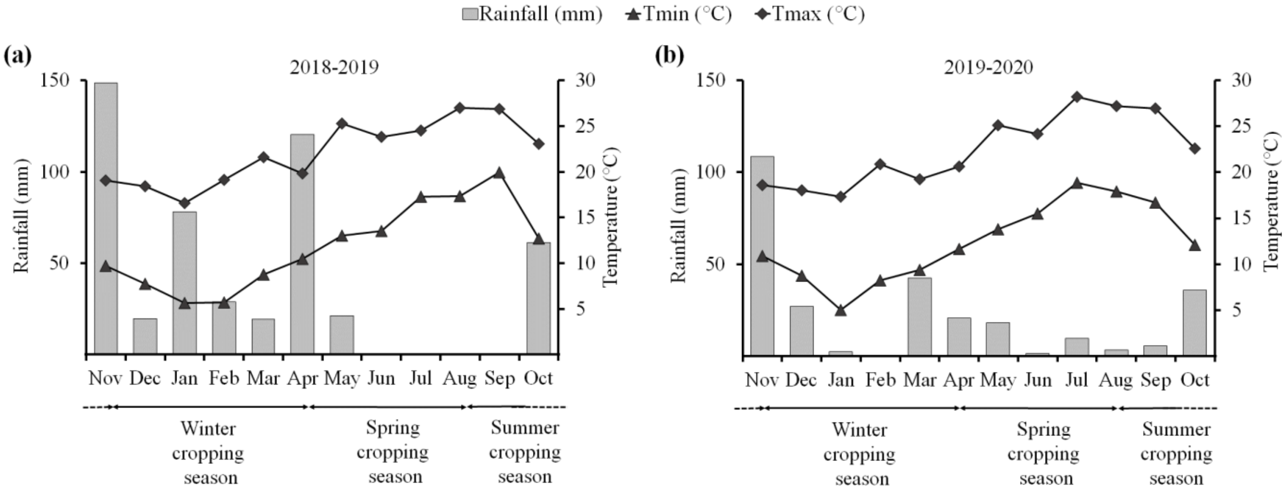


Figure 1. Temperatures and rainfall of the studied area for the first experimental season (2018-2019) (a) and the second season (2019-2020) (b)

Corn and soybean were equipped with a drip irrigation system. The driplines were separated by 1.1 m with 1 l h^{-1} emitters and 0.4 m as emitters spacing. The irrigation amounts were around 424 and 417 mm for the spring and summer seasons of 2018-2019 and 2019-2020, respectively.

The soil was supplied with 268 kg ha^{-1} of N, 33 kg ha^{-1} of P, and 197 kg ha^{-1} of K for corn. The soybean received 64 kg ha^{-1} of N, 26 kg ha^{-1} of P, and 83 kg ha^{-1} of K. Ammonitrate, chloride of potassium, and 15-30-10 were used as sources of nutrients. For different crop successions, corn received 35 kg ha^{-1} of zinc sulfate, 5 kg ha^{-1} of manganese sulfate, and 1 kg ha^{-1} copper sulfate. Weeds were controlled manually for both crops. The fungal disease (*Setosphaeria turcica)* was controlled for corn with epoxiconazole.

2.4 Measurements

2.4.1 Forage biomass production

For oat and berseem, the harvest was carried out at flowering. The pea/triticale association was harvested at the pod feeling of the pea. For these winter crops, the biomass of five areas of 0.25 m^2 per experimental plot was cut, oven-dried at 60 °C until constant weight, and weighed.

Corn was harvested at 33% of dry matter, and soybean was harvested at 28%. For both species, an area of 2.2 m^2 per experimental plot was cut, crushed, and oven-dried to determine the dry matter weight.

2.4.2 Mineral elements uptake

The dry matter of each forage crop was crushed to determine the mineral content. A sample of 0.6 g of each forage was digested with a mixture of salicylic and sulfuric acids to determine the N, P, K, and Mg concentrations (Dhassi et al., 2021). N and P concentrations were determined using a continuous flow analyzer (Skalar San ++, Skalar, Breda, Netherlands). The K and Mg contents were determined using an atomic absorption spectrophotometer (Varian AA 240, Fast Sequential, air acetylene flame).

In addition, a subsample of 2 g was digested with 20 ml of a tri-acid mixture (350 ml of nitric acid + 40 ml of perchloric acid + 30 ml of sulfuric acid) to determine zinc (Zn), manganese (Mn), iron (Fe), and copper (Cu) concentrations (Amlal et al., 2022).

Zinc, Fe, Mn, and Cu were analyzed using an atomic absorption spectrophotometer (Varian AA 240 Fast Sequential ; air acetylene flame).

The total uptake of each nutrient element was calculated according to the Formula 1.

$$\text{Nutrient uptake (kg ha}^{-1}\text{)} = \text{Nutrient content (\% dry matter)} \times \text{Total aerial biomass (kg ha}^{-1}\text{)} \quad [1]$$

2.4.3 Forage quality analyses

The crude protein (CP) of each harvested plant was calculated for each experimental plot from the nitrogen content (Formula 2) (Chang & Zhang, 2017).

$$\text{CP (\% dry matter)} = \text{N content (\% dry matter)} \times 6.25 \quad [2]$$

Then, the produced crude protein per hectare for each crop was determined using the Formula 3.

$$\text{Produced CP (T ha}^{-1}\text{)} = \text{CP content (\% dry matter)} \times \text{Total aerial biomass (T ha}^{-1}\text{)} \quad [3]$$

Where CP content is the percentage of dry matter of plant crude protein.

To assess the forage energy content, crude fat (EE), crude fiber (CF), neutral detergent fiber (NDF), and organic matter digestibility (OMd) were determined for each harvested plant using a near-infrared reflectance spectrophotometer (InfraXact, FOSS). Thereafter, the net energy for lactation (in MJ kg^{-1} dry $matter^{-1}$) was calculated using the Formula 4, 5, 6, and 7 (Sauvant et al., 2004). The net energy for lactation was determined by Formula 4.

$$\text{Net energy for lactation} = [0.6+0.24 \times (\frac{\text{Metabolisable energy}}{\text{Gross energy}} - 0.57)] \times \text{Metabolisable energy} \quad [4]$$

The gross energy (in MJ kg^{-1} dry $matter^{-1}$) was determined by Formula 5.

$$\text{Gross energy} = 17.3 + 0.0617 \times \text{CP} + 0.2193 \times \text{EE} + 0.0387 \times \text{CF} - 0.1867 \times \text{MM} + \Delta \quad [5]$$

Where CP is the percentage of crude protein in dry matter, EE is the percentage of ether extract (crude fat) in dry matter, Cf is the percentage of crude fiber in dry matter, MM is the percentage of mineral matter in dry matter. It was determined by calcination at 550 °C of the dry sample, and Δ is correction coefficient (positive or negative) to be used according to the type of feed material.

The metabolisable energy (in MJ kg^{-1} dry $matter^{-1}$) was calculated using Formula 6.

$$\text{Metabolisable energy} = \text{GE} \times \text{Ed} \times (86.38 - 0.099 \times \text{CFo} - 1.96 \times \text{CPo}) \quad [6]$$

Where GE is gross energy (determined by Formula 5), Ed is the digestibility of the gross energy (in %) was calculated using Formula 7, CFo is the percentage of crude fiber in organic matter, and CPo is the percentage of crude protein in organic matter.

$$\text{Ed} = \text{OMd} - 3.94 + 0.104 \times \text{CP} + 0.149 \times \text{EE} + 0.022 \times \text{NDF} - 0.244 \times \text{MM} \quad [7]$$

Where OMd is the percentage of organic matter digestibility, CP is the percentage of crude protein in dry matter, EE is the percentage of ether extract (crude fat) in dry matte, NDF is the percentage of neutral detergent fiber in dry matter, and MM is the percentage of mineral matter in dry matter.

The total net energy for lactation was determined for each crop using Formula 8.

$$\text{Total NEL (MJ ha}^{-1}) = \text{NEL content (MJ kg}^{-1}\text{dry matter}^{-1}) \times \text{Total aerial biomass (kg ha}^{-1}) \quad [8]$$

Where NEL is net energy for lactation (Formula 4), and total aerial biomass is the total weight of aerial biomass in a hectare.

2.4.4 Soil organic matter and mineral contents

After harvesting the summer crop for each studied season (2018-2019 and 2019-2020), soil samples (0- 30 cm) were taken from the experimental plot to determine the organic matter, macronutrients (N, P, K, and Mg), and micronutrients (Cu, Fe, Mn, and Zn) contents. The organic matter in soil was determined using the acid-wet oxidation method. The contents of N and P in soil were determined using the Kjeldahl and Olsen extraction methods, respectively. The ammonium acetate extraction was used to determine the soil K and Mg contents (Amlal et al., 2020). The DTPA extraction was used to determine the soil Cu, Fe, Mn, and Zn contents (Darrhal et al., 2022).

2.5 Statistical analysis

The produced biomass, nutrient uptake, and quality parameters were analyzed using three-way ANOVA (crop rotation, year, and block factors). A two-way ANOVA (crop rotation and block factors) was performed for each soil parameter at the end of an annual crop rotation. The comparison of means was carried out using the Student-Newman-Keuls test at P <0.05. All the statistical analyses were performed using the program SPSS (Version 20.0).

3. RESULTS

3.1 Forage biomass production

The total forage biomass produced by the three successive crops was significantly affected he crop succession during the studied years (Table 2). The oat-corn-corn and pea/triticale-corn-corn successions resulted in the highest dry biomass production (46.5 t ha^{-1} $year^{-1}$). The berseem-corn-soybean succession recorded the lowest dry biomass (30.8 t ha^{-1} $year^{-1}$). The biomass produced by each crop succession was similar for 2018-2019 and 2019-2020.

Corn and soybean of the spring cropping season produced approximately 54% of the total biomass (Table 2 and Table 3). For this cropping season, corn produced more biomass (23.2 t ha^{-1}) than soybean (9.5 t ha^{-1}) (Table 3). The winter cropping season had the lowest contribution to the total forage production with approximately 5% for berseem, 10% for oat, and 12% for pea/triticale. The pea/triticale association yielded the highest winter biomass production (5.0 t ha^{-1}). The lowest winter biomass was recorded for berseem (2 t ha^{-1}). During the summer growing season, the highest biomass production was recorded for corn (18.2 t ha^{-1}) at crop successions of oat-corn-corn, pea/triticale-corn-corn, and oat-soybean-corn. In contrast, summer soybean recorded the lowest biomass production (6.2 t ha^{-1}) (Table 3).

3.2 Forage net energy for lactation and crude protein

Concerning the forage quality, the annual produced net energy for lactation was significantly influenced by the crop succession (Table 4). The oat-corn-corn and pea/triticale-corn-corn successions recorded the highest net energy for lactation (approximately 303 10^3 MJ ha^{-1} $year^{-1}$). The crop succession based on one corn: oat-soybean-corn and berseem-corn-soybean recorded the lowest net energy for lactation (195.5 10^3 MJ ha^{-1} $year^{-1}$).

Table 2. Forage dry biomass production at different crop successions per year.

Crop successions* during a year	Dry biomass at harvest (t ha^{-1} $year^{-1}$)		
	2018-2019	2019-2020	Means
Fallow-Corn-Corn	35.9 ± 2.9 bc	36.2 ± 6.4 b	36.1 ± 4.7 c
Oat-Corn-Corn	45.8 ± 2.9 a	46.1 ± 3.1 a	46.0 ± 2.8 a
Berseem-Corn-Corn	41.2 ± 8.4 ab	42.2 ± 3.6 a	41.7 ± 6.1 b
Pea/Triticale-Corn-Corn	47.7 ± 1.7 a	46.0 ± 3.1 a	46.9 ± 2.5 a
Oat-Soybean-Corn	34.3 ± 3.8 c	31.8 ± 3.6 b	33.0 ± 3.7 cd
Berseem-Corn-Soybean	27.1 ± 1.4 d	34.5 ± 4.2 b	30.8 ± 4.9 d

Remarks: *Crop successions were conducted during 2018-2019 and repeated on the same plots in 2019-2020. Values are means ± standard deviation (n=5). For each growing season, means followed by the same letters are not significantly different. In a crop succession ($Crop_1$-$Crop_2$-$Crop_3$), the winter production was designed by the first crop, the spring production was designed by the second crop, and the summer production was designed by the third crop.

Table 3. Forage biomass production per crop for different crop successions during both experimental years

Crop successions* during a year	Winter crops	Dry biomass at harvest (t ha^{-1}) 2018-2019	2019-2020	Means
Fallow-Corn-Corn	Fallow	-	-	-
Oat-Corn-Corn	Oat	4.1 ± 0.7 b	3.7 ± 0.3 a	3.9 ± 0.5 b
Berseem-Corn-Corn	Berseem	2.5 ± 0.5 c	1.6 ± 0.3 b	2.0 ± 0.6 c
Pea/Triticale-Corn-Corn	Pea/Triticale	6.1 ± 0.4 a	4.0 ± 0.3 a	5.0 ± 1.2 a
Oat-Soybean-Corn	Oat	4.1 ± 0.3 b	4.0 ± 0.4 a	4.1 ± 0.3 b
Berseem-Corn-Soybean	Berseem	2.0 ± 0.5 c	1.8 ± 0.2 b	1.9 ± 0.4 c
	Spring crops			
Fallow-Corn-Corn	Corn	18.4 ± 1.9 a	22.5 ± 3.7 a	20.5 ± 3.5 b
Oat-Corn-Corn	Corn	22.1 ± 2.6 a	28.2 ± 2.5 a	25.1 ± 4.0 a
Berseem-Corn-Corn	Corn	21.8 ± 2.6 a	26.5 ± 3.9 a	24.2 ± 4.0 a
Pea/Triticale-Corn-Corn	Corn	19.9 ± 3.0 a	27.6 ± 3 a	23.7 ± 4.9 ab
Oat-Soybean-Corn	Soybean	9.3 ± 1.3 b	9.6 ± 1 b	9.5 ± 1.1 c
Berseem-Corn-Soybean	Corn	18.9 ± 1.9 a	26.5 ± 4.1 a	22.7 ± 5.0 ab
	Summer crops			
Fallow-Corn-Corn	Corn	17.5 ± 1.2 a	13.7 ± 2.9 b	15.6 ± 2.9 b
Oat-Corn-Corn	Corn	19.6 ± 1.8 a	14.3 ± 1.9 b	17 ± 3.3 ab
Berseem-Corn-Corn	Corn	16.9 ± 6.2 a	14.1 ± 1.7 b	15.5 ± 4.6 b
Pea/Triticale-Corn-Corn	Corn	21.6 ± 2.7 a	14.5 ± 1.2 b	18.1 ± 4.2 ab
Oat-Soybean-Corn	Corn	20.8 ± 3.8 a	18.2 ± 3.2 a	19.5 ± 3.5 a
Berseem-Corn-Soybean	Soybean	6.2 ± 0.8 b	6.2 ± 0.8 c	6.2 ± 0.8 c

Remarks: *Crop successions were conducted during 2018-2019 and repeated on the same plots in 2019-2020. Values are means ± standard deviation (n=5). For each growing season, means followed by the same letters are not significantly different. In a crop succession ($Crop_1$-$Crop_2$-$Crop_3$), the winter production was designed by the first crop, the spring production was designed by the second crop, and the summer production was designed by the third crop.

Table 4. Forage net energy for lactation produced for each experimental year at different crop successions

Crop successions* during a year	Annual produced net energy for lactation (1000 MJ ha^{-1} year^{-1}) 2018-2019	2019-2020	Means
Fallow-Corn-Corn	228.0 ± 18.9 b	240.2 ± 42.0 b	234.1 ± 31.4 c
Oat-Corn-Corn	293.8 ± 18.8 a	311.0 ± 20.8 a	302.4 ± 20.8 a
Berseem-Corn-Corn	262.0 ± 50.4 a	278.8 ± 25.0 a	270.4 ± 38.5 b
Pea/Triticale-Corn-Corn	297.8 ± 11.8 a	309.5 ± 21.3 a	303.6 ± 17.3 a
Oat-Soybean-Corn	193.4 ± 21.1 c	191.3 ± 22.3 c	192.3 ± 20.5 d
Berseem-Corn-Soybean	173.6 ± 10.5 c	223.6 ± 28.9 bc	198.6 ± 33.4 d

Remarks: *Crop successions were conducted during 2018-2019 and repeated on the same plots in 2019-2020. Values are means ± standard deviation (n=5). For each growing season, means followed by the same letters are not significantly different. In a crop succession ($Crop_1$-$Crop_2$-$Crop_3$), the winter production was designed by the first crop, the spring production was designed by the second crop, and the summer production was designed by the third crop.

The annual produced net energy for lactation was similar for 2018-2019 and 2019-2020 for each crop succession. Similarly, the annual produced crude protein was significantly related to the crop succession (Table 5). The oat-corn-corn, pea/triticale-corn-corn, and oat-soybean-corn successions recorded the highest crude protein levels (approximately 3.9 t ha^{-1} year^{-1}). The fallow-corn-corn resulted in the lowest crude protein (2.7 t ha^{-1} year^{-1}). The crude protein level was similar for 2018-2019 and 2019-2020 at each crop succession.

3.3 Forage nutrient uptake

The annual N uptake was significantly influenced by crop succession (Table 6). The oat-corn-corn, pea/triticale-corn-corn, and oat-soybean-corn successions recorded the highest N uptake levels (around 627 kg ha^{-1} year^{-1}). The fallow-corn-corn succession resulted in the lowest N uptake (435 kg ha^{-1} year^{-1}). Similarly, the annual P, K, and Mg uptakes were significantly influenced by crop succession (Table 6**Table 6**). The oat-corn-corn, berseem-corn-corn, and pea/triticale-corn-corn successions recorded the highest P uptake levels (approximately 94 kg ha^{-1} year^{-1}). The fallow-corn-corn and berseem-corn-soybean successions had the lowest P uptake (77 kg ha^{-1} year^{-1}). Concerning the K uptake, the oat-corn-corn and pea/triticale-corn-corn successions recorded the highest K uptake levels (approximately 484 kg ha^{-1} year^{-1}) (Table 6). The fallow-corn-corn and berseem-corn-soybean successions resulted in the lowest K uptake (335 kg ha^{-1} year^{-1}). Concerning Mg uptake, the oat-soybean-corn succession recorded the highest Mg uptake value (60 kg ha^{-1} year^{-1}). The fallow-corn-corn succession resulted in the lowest Mg uptake (45 kgha^{-1}year^{-1}).

Table 5. Annual produced crude protein (t ha^{-1} year^{-1}) for the both experimental years at different crop successions.

Crop successions* during a year	Annual produced crude protein (t ha^{-1} year^{-1})		
	2018-2019	2019-2020	Means
Fallow-Corn-Corn	2.7 ± 0.2 d	2.8 ± 0.5 b	2.7 ± 0.4 c
Oat-Corn-Corn	3.8 ± 0.2 b	3.6 ± 0.3 a	3.7 ± 0.3 a
Berseem-Corn-Corn	3.3 ± 0.7 c	3.3 ± 0.3 ab	3.3 ± 0.5 b
Pea/Triticale-Corn-Corn	4.2 ± 0.2 ab	3.6 ± 0.2 a	3.9 ± 0.4 a
Oat-Soybean-Corn	4.4 ± 0.4 a	3.8 ± 0.4 a	4.1 ± 0.5 a
Berseem-Corn-Soybean	3.1 ± 0.1 cd	3.4 ± 0.4 ab	3.2 ± 0.3 b

Remarks: *Crop successions were conducted during 2018-2019 and repeated on the same plots in 2019-2020. Values are means ± standard deviation (n=5). For each growing season, means followed by the same letters are not significantly different. In a crop succession ($Crop_1$-$Crop_2$-$Crop_3$), the winter production was designed by the first crop, the spring production was designed by the second crop, and the summer production was designed by the third crop.

Table 6. Total macronutrients uptake for the both experimental years at different forage crop successions.

Crop successions* during a year	N (kg ha^{-1} year^{-1})	P (kg ha^{-1} year^{-1})	K (kg ha^{-1} year^{-1})	Mg (kg ha^{-1} year^{-1})
	2018-2019			
Fallow-Corn-Corn	426 ± 33 d	59 ± 12 ab	409 ± 59 c	49 ± 20 a
Oat-Corn-Corn	608 ± 38 b	70 ± 6 a	610 ± 47 a	57 ± 6 a
Berseem-Corn-Corn	528 ± 112 c	65 ± 18 a	503 ± 96 b	54 ± 13 a
Pea/Triticale-Corn-Corn	671 ± 34 ab	76 ± 13 a	572 ± 36 ab	55 ± 4 a
Oat-Soybean-Corn	708 ± 61 a	72 ± 12 a	519 ± 35 b	64 ± 7 a
Berseem-Corn-Soybean	496 ± 23 cd	49 ± 7 b	357 ± 25 c	48 ± 6 a
	2019-2020			
Fallow-Corn-Corn	444 ± 84 b	93 ± 14 b	278 ± 55 b	41 ± 7 b
Oat-Corn-Corn	585 ± 60 a	120 ± 9 a	383 ± 48 a	49 ± 5 ab
Berseem-Corn-Corn	520 ± 59 ab	117 ± 13 ab	309 ± 25 b	47 ± 3 ab
Pea/Triticale-Corn-Corn	571 ± 34 a	116 ± 7 ab	372 ± 31 a	48 ± 3 ab
Oat-Soybean-Corn	616 ± 67 a	106 ± 12 ab	320 ± 21 b	55 ± 5 a
Berseem-Corn-Soybean	540 ± 60 ab	106 ± 18 ab	296 ± 23 b	49 ± 4 ab
	Means of 2018-2019 and 2019-2020			
Fallow-Corn-Corn	435 ± 61 c	76 ± 22 b	343 ± 88 c	45 ± 15 b
Oat-Corn-Corn	596 ± 49 a	95 ± 28 a	496 ± 128 a	53 ± 7 ab
Berseem-Corn-Corn	524 ± 84 b	91 ± 31 a	406 ± 121 b	50 ± 9 ab
Pea/Triticale-Corn-Corn	621 ± 62 a	96 ± 23 a	472 ± 110 a	51 ± 5 ab
Oat-Soybean-Corn	662 ± 78 a	89 ± 21 ab	419 ± 108 b	60 ± 7 a
Berseem-Corn-Soybean	518 ± 49 b	78 ± 33 b	327 ± 39 c	48 ± 5 ab

Remarks: *Crop successions were conducted during 2018-2019 and repeated on the same plots in 2019-2020. Values are means ± standard deviation (n=5). For each growing season, means followed by the same letters are not significantly different. In a crop succession ($Crop_1$-$Crop_2$-$Crop_3$), the winter production was designed by the first crop, the spring production was designed by the second crop, and the summer production was designed by the third crop.

On the other hand, the pea/triticale-corn-corn succession recorded the highest uptake of Cu (0.22 kg ha^{-1} year^{-1}), Fe (6.1 kg ha^{-1} year^{-1}), Mn (0.5 kg ha^{-1} year^{-1}), and Zn (1.4 kg ha^{-1} year^{-1}) (Table 7). In contrast, the berseem-corn-soybean succession had the lowest uptakes of Cu (0.15 kg ha^{-1} year^{-1}), Fe (2.9 kg ha^{-1} year^{-1}), Mn (0.2 kg ha^{-1} year^{-1}), and Zn (0.9 kg ha^{-1} year^{-1}).

3.4 Soil organic matter and nutrient contents

At the end of each experimental year, the organic matter level was similar for different crop successions (Fig. 2a). The organic matter levels were 1.0% and 0.9% at the end of 2018-2019 and 2019-2020, respectively. Similarly, the residual N in the soil was not significantly influenced by the crop succession of each studied season (Fig. 2b). The total N was approximately 0.06 % and 0.05% at the end of the 2018-2019 and 2019-2020 seasons, respectively. The total N and organic matter were not significantly reduced between the growing seasons, although a declining tendency was noticed for each crop succession.

Similarly, the residual P and Mg levels were significantly similar in the soil of different crop successions at the end of each experimental year (Fig. 3a and 3c). The P levels were 72 mg kg^{-1} and 60 mg kg^{-1} at the end of 2018-2019 and 2019-2020, respectively. The Mg contents were approximately 82 mg kg^{-1} and 67 mg kg^{-1} for 2018-2019 and 2019-2020, respectively. For each crop succession, no significant difference in the P content in the soil between the studied years was recorded, although a reduction tendency was noticed.

Table 7. Total micronutrients uptake for the both experimental years at different succession systems.

Crop successions* during a year	Cu (kg ha^{-1} year^{-1})	Fe (kg ha^{-1} year^{-1})	Mn (kg ha^{-1} year^{-1})	Zn (kg ha^{-1} year^{-1})
	2018-2019			
Fallow-Corn-Corn	0.2 ± 0.04 c	5.1 ± 1.8 a	0.4 ± 0.1 b	0.7 ± 0.1 b
Oat-Corn-Corn	0.2 ± 0.03 b	5.9 ± 1.4 a	0.6 ± 0.1 a	0.9 ± 0.1 a
Berseem-Corn-Corn	0.2 ± 0.02 ab	6.8 ± 4.1 a	0.5 ± 0.1 a	0.9 ± 0.2 a
Pea/Triticale-Corn-Corn	0.2 ± 0.05 a	9.2 ± 7.2 a	0.5 ± 0.2 a	1.0 ± 0.1 a
Oat-Soybean-Corn	0.2 ± 0.02 c	6.0 ± 1.5 a	0.6 ± 0.1 a	0.6 ± 0.1 b
Berseem-Corn-Soybean	0.1 ± 0.01 c	3.5 ± 0.9 a	0.4 ± 0.1 b	0.6 ± 0.1 b
	2019-2020			
Fallow-Corn-Corn	0.1 ± 0.02 c	4 ± 3.7 a	0.3 ± 0.1 b	1.5 ± 0.3 a
Oat-Corn-Corn	0.2 ± 0.02 ab	3 ± 0.3 a	0.6 ± 0.1 a	2 ± 0.7 a
Berseem-Corn-Corn	0.2 ± 0.01 bc	2.1 ± 0.7 a	0.3 ± 0.1 b	1.9 ± 0.5 a
Pea/Triticale-Corn-Corn	0.2 ± 0.02 a	3.1 ± 1.1 a	0.5 ± 0.1 a	1.9 ± 0.3 a
Oat-Soybean-Corn	0.2 ± 0.03 bc	2.9 ± 0.9 a	0.6 ± 0.1 a	1.7 ± 0.5 a
Berseem-Corn-Soybean	0.2 ± 0.02 bc	2.3 ± 0.9 a	0.04 ± 0.004 c	1.2 ± 0.2 a
	Means of 2018-2019 and 2019-2020			
Fallow-Corn-Corn	0.2 ± 0.03 c	4.5 ± 2.8 ab	0.3 ± 0.1 b	1.1 ± 0.5 ab
Oat-Corn-Corn	0.2 ± 0.02 b	4.4 ± 1.8 ab	0.6 ± 0.1 a	1.5 ± 0.7 a
Berseem-Corn-Corn	0.2 ± 0.03 b	4.5 ± 3.7 ab	0.4 ± 0.2 b	1.4 ± 0.6 a
Pea/Triticale-Corn-Corn	0.2 ± 0.04 a	6.1 ± 5.8 a	0.5 ± 0.1 a	1.4 ± 0.5 a
Oat-Soybean-Corn	0.2 ± 0.03 bc	4.4 ± 2.0 ab	0.6 ± 0.1 a	1.1 ± 0.6 ab
Berseem-Corn-Soybean	0.1 ± 0.02 c	2.9 ± 1.1 b	0.2 ± 0.2 c	0.9 ± 0.3 b

Remarks: *Crop successions were conducted during 2018-2019 and repeated on the same plots in 2019-2020. Values are means ± standard deviation (n=5). For each growing season, means followed by the same letters are not significantly different. In a crop succession ($Crop_1$-$Crop_2$-$Crop_3$), the winter production was designed by the first crop, the spring production was designed by the second crop, and the summer production was designed by the third crop.

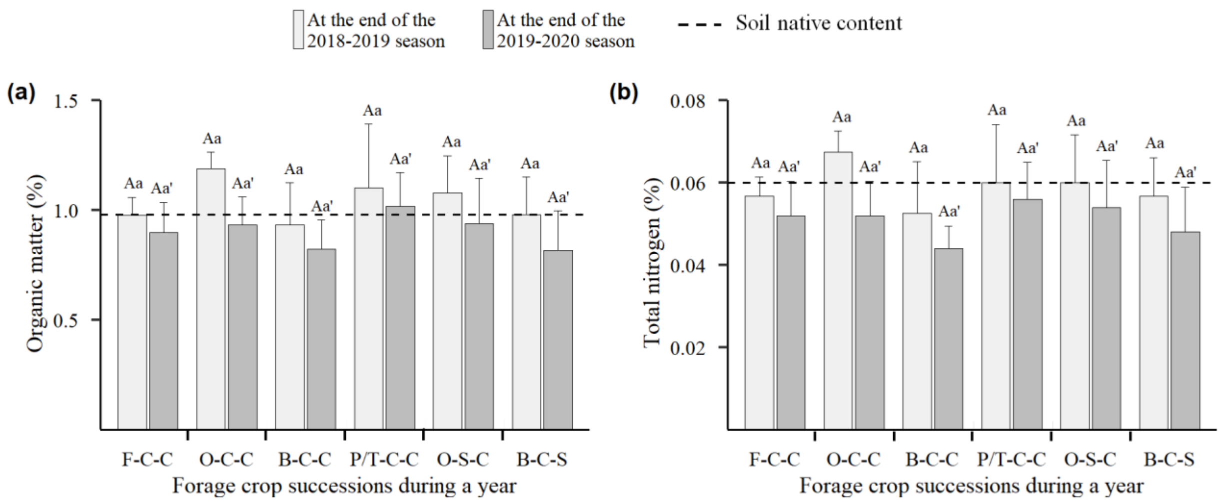
In contrast, the Mg varied significantly between the experimental years according to the crop successions. Indeed, the lowest levels were recorded at the end of the second experimental year (2019-2020) for the successions of fallow-corn-corn, oat-corn-corn, pea/triticale-corn-corn, and berseem-corn-soybean.

The soil K content was significantly different between the crop successions only at the end of 2019-2020 (Fig. 3b). Indeed, the soil of fallow-corn-corn and oat-soybean-corn successions recorded the highest K level (approximately 111 mg kg^{-1}). The soil occupied by berseem-corn-soybean had the lowest K content (66 mg kg^{-1}). In addition, the levels of K showed decreases of 41%, 30%, and 43% for oat-corn-corn, berseem-corn-corn, and berseem-corn-soybean, respectively, at the end of 2019-2020 compared to the end of 2018-2019. On the other hand, the residual contents of Fe and Cu in the soil were significantly similar for different crop successions at the end of each studied year (Fig. 3f and 3d). The Cu levels were around 0.64 mg kg^{-1}, and the Fe levels were around 10.6 mg kg^{-1} for all the crop successions and years.

The Mn level in the soil decreased significantly over the studied years only for the crop successions containing oat (oat-corn-corn and oat-soybean-corn). Indeed, the Mn levels recorded at the end of 2018-2019 decreased by 37.9% for the succession of oat-corn-corn and by 30.8% for oat-soybean-corn at the end of 2019-2020. Concerning the Zn residual content in the soil, it was affected by the crop succession only during the first studied year (2018-2019) (Fig. 3g). Oat-corn-corn succession recorded the highest Zn level (8.3 mg kg^{-1}). The berseem-corn-corn succession had the lowest soil Zn content (5.5 mg kg^{-1}).

4. DISCUSSION

The intensification of the forage cropping system based on corn became a common production strategy in the southern Mediterranean to ensure the increasing forage demand of the livestock. This investigation revealed that intensive forage production based on two successive cropping seasons of corn (spring and summer) after a rainfed forage crop in winter ensured the high forage biomass production. The highest cumulative dry biomass was recorded for successions of oat-corn-corn (45.8 t ha^{-1} year^{-1}) and pea/triticale-corn-corn (47.7 t ha^{-1} year^{-1}). High biomass production was reported for annual intensive crop successions including forages legumes and cereal (Manoj et al., 2021). The results of the winter cropping season emphasize the importance of introducing a rainfed forage crop during winter, particularly oat and the association of pea/triticale. However, the rainfed forage crops could develop low biomass in a dry winter season that could serve as green manure to incorporate into the soil. The green manure supply in sandy soil could help to enhance the organic matter and the nitrogen level (Fernandes et al., 2020; Roper et al., 2012; Saleh, 2013). The forage cropping system based on one corn cycle (berseem-corn-soybean) had the lowest yield (30.8 t ha^{-1} year^{-1}). In fact, the insertion of soybean in the spring or the summer seasons did not reveal similar productivity as the forage corn. Hence, further experiments are required to evaluate other forage crops instead of corn during the spring and the summer seasons, particularly fodder beet and associations of corn with legume crops such as lablab (*Lablab purpureus*) and cowpea (*Vigna unguiculata*). On the other hand, the intensive cropping systems based on corn can be sustainable in terms of economic indicators (Christiansen et al., 2015) and social advantages (Prospero-Bernal et al., 2017).



F-C-C: Fallow-Corn-Corn; **O-C-C:** Oat-Corn-Corn; **B-C-C:** Berseem-Corn-Corn; **P/T-C-C:** Pea/Triticale-Corn-Corn; **O-S-C:** Oat-Soybean-Corn; **B-C-S:** Berseem-Corn-Soybean.

Figure 2. Soil organic matter (a) and total nitrogen content (b) after each succession for both studied seasons. Crop successions were conducted during 2018-2019 and repeated on the same plots in 2019-2020. Vertical bars denote standard deviations (n=5). For each crop succession, means followed by the same capital letters are not significantly different. For each growing season, means followed by the same lowercase letters are not significantly different. In a crop succession ($Crop_1$-$Crop_2$-$Crop_3$), the winter production was designed by the first crop, the spring production was designed by the second crop, and the summer production was designed by the third crop

However, we cannot neglect the negative impact of corn monocropping on soil preservation even though a rainfed forage crop in winter (legumes or association of cereal/legume) is introduced after summer corn. Many authors reported that monocropping forage systems based on corn resulted in soil nutrient depletion (Perera & Weerasinghe, 2014). Our study revealed a significant decrease in the bioavailability of K after two production years, particularly for the crop succession containing oat or berseem in winter. The K decline can be explained by both the low cation exchange capacity (8.3 meq 100 g^{-1}) and low clay level (7.7%) of the sandy soil. The K depletion trend in sandy soil can depress crop production, especially for cereal species over the years (Srinivasarao et al., 2014). Thus, attention must be devoted to supplying an additional K continuously to make up for the K plant uptake and preserve an adequate K level in the soil (Table 6). In addition, the application of dairy cattle manures, mulching, and clay is a requested solution to preserve the sandy soil.

Similarly, a significant decrease in Mg and Mn was noticed with some crop successions containing corn, oat, and berseem. These results are in contrast with those of Neugschwandtner et al. (2022) who reported no significant effect of rotations on the Mg level in a 15-year study. However, the absence of a significant influence of crop successions on the organic matter and other nutrients (P, Cu, Fe, and Zn) can be explained by the restricted number of successive studied seasons (2 years). Such short-term evaluation may not result in noticeable soil nutrient depletion. The depletion tendency of N and P in soil was significant in a 41-year study conducted on a rice-wheat rotation in a loamy-sand soil (Ram et al., 2016). However, we cannot neglect the decreasing trend of these nutrient levels in the soil over both tested years (Fig. 2 and 3). The soil nutrient depletion tendency can be explained by the low nutrient retention capacity (CEC=8.3 meq 100 g^{-1}) of sandy soil and plant uptake of macro and micronutrients. Such a depletion tendency was more pronounced with the successions of oat-corn-corn concerning K, Mg, and Mn and berseem-corn-soybean concerning k and Mg. Concerning the soil N status, the legumes did not help enhance the N level in the studied sandy soil, particularly for berseem and soybean. However, we cannot deny the role of legume forage crops in reducing the N supply compared to cereals. Thus, successions containing legumes appeared to be environment-friendly compared to cereals in reducing N leaching (Masoni et al., 2015).

Concerning the forage quality, two successive corn productions per year enhanced the net energy for lactation. This net energy was increased due to the inclusion of a winter forage, particularly the oat and pea/triticale association. Indeed, oat-corn-corn and pea/triticale-corn-corn successions were the most productive in terms of total net energy for lactation (approximately 303 10^3 MJ ha^{-1} $year^{-1}$). The superiority of these successions was mainly related to the high amount of energy contained in spring corn (7.0 MJ kg^{-1} dry $matter^{-1}$), summer corn (6.0 MJ kg^{-1} dry $matter^{-1}$), oat (7.3 MJ kg^{-1} dry $matter^{-1}$), and pea/triticale association (6.7 MJ kg^{-1} dry $matter^{-1}$). Similar net energy levels were reported for the corn and pea/triticale association by Gill and Omokanye (2018). In contrast, the low net energy of legume crops did not promote the produced net energy of crop succession, particularly for berseem (5.5 MJ kg^{-1} dry $matter^{-1}$) and soybean (5.0 MJ kg^{-1} dry $matter^{-1}$). Hence, the lowest total net energy for lactation (around 195.5 10^3 MJ ha^{-1} $year^{-1}$)

was recorded for oat-soybean-corn and berseem-corn-soybean.

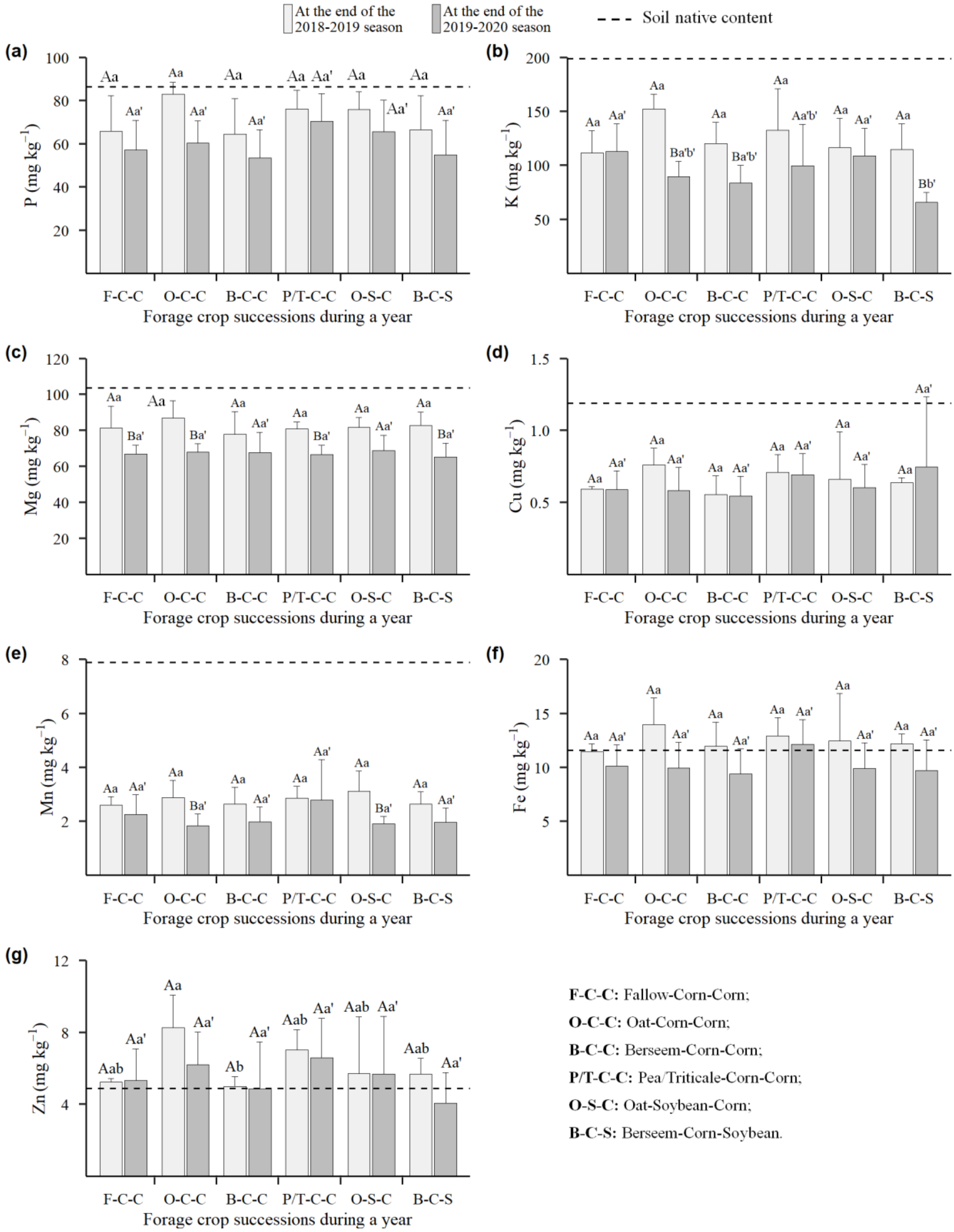


Figure 3. Soil macronutrients (P (a), K (b), and Mg (c) and micronutrients (Cu (d), Mn (e), Fe (f), and Zn (g)) contents after each succession for both studied seasons. Crop successions were conducted during 2018-2019 and repeated on the same plots in 2019-2020. Vertical bars denote standard deviations (n=5). For each crop succession, means followed by the same capital letters are not significantly different. For each growing season, means followed by the same lowercase letters are not significantly different. In a crop succession ($Crop_1$-$Crop_2$-$Crop_3$), the winter production was designed by the first crop, the spring production was designed by the second crop, and the summer production was designed by the third crop.

Besides the net energy for lactation, the highest annual production of crude protein was recorded for oat-corn-corn, pea/triticale-corn-corn, and oat-soybean-corn successions (approximately 3.9 t ha^{-1} year^{-1}). The high biomass of corn compensated for its low crude protein content (around 7% of dry matter). However, the fallow-corn-corn succession (based only on two corn seasons) had the lowest annual produced crude protein (2.7 t ha^{-1} $year^{-1}$). This result revealed the importance of a winter forage crop (oat or pea/triticale) in promoting the crude protein production of a crop succession.

5. CONCLUSION

This study aimed to evaluate the productivity, quality, and nutrient uptake of different intensive forage crop rotations based on corn in sandy soil (northern Morocco). The results of the field experiment shed light on the responses of forage crops in the different studied rotations. The intensive forage cropping systems based on a succession of spring and summer corn after a winter crop (oat or pea/triticale association) ensure a higher biomass production with maximum net energy for lactation and total crude protein. Oat-corn-corn and pea/triticale-corn-corn successions produced the highest dry biomass (46.5 t ha^{-1} $year^{-1}$) and net energy for lactation (303 10^3 MJ ha^{-1} $year^{-1}$). The inclusion of soybean in the system was beneficial only for crude protein production since this crop was unable to rival the high-produced biomass and energy of corn. However, we cannot neglect the negative impact of such intensive production on the sustainability of the cropping system, particularly the soil nutrient depletion of K, Mn, and Mg. Therefore, an adequate soil amendment and nutrient supply should be ensured for the forage cropping system in sandy soil.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests that may appear and influence the work reported in this paper.

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