Research Findings

Photo 1. Alfalfa (*Medicago sativa*). Photo by the authors.

Polyhalite Enhances Alfalfa Production, Quality, and Environmental Footprints, Reims, France

Morell, F.J.[(1)*], M. de Villenaut[(2)], and F. Carnec[(3)]

Abstract

Similar to most rainfed crops, alfalfa (*Medicago sativa*) is assumed to benefit from a balanced macronutrient supply. Polyhalite is a natural mineral fertilizer consisting of a hydrated sulfate of potassium (K), calcium (Ca), and magnesium (Mg) with the formula: $K_2Ca_2Mg(SO_4)_4 \cdot 2(H_2O)$. Polyhalite is less water soluble than conventional nutrient sources and is, therefore, suitable as a supply of these four nutrients during rainy growing seasons. Due to its relatively low K content (14%), fortification of polyhalite application with alternative K sources, such as KCl (potassium chloride) should be considered. The objectives of the present study were to examine the response of alfalfa yield and quality to increasing proportions of polyhalite, and to estimate the crop's carbon footprint, compared to KCl alone and to an unfertilized control. A field trial was established at Vésigneul-sur-Marne, France, during the second and third years (2019-2020) of a perennial alfalfa field. An annual dose of 300 kg K_2O ha^{-1} was supplied to four treatments through 0, 200, 405, or 800 kg polyhalite ha^{-1} and 500, 450, 405, and 310 kg KCl,

[(1)]IPI Coordinator for Europe, International Potash Institute, Zug, Switzerland

[(2)]ICL, North France, France

[(3)]IPI Coordinator for France, International Potash Institute, Zug, Switzerland

*Corresponding author: Francisco.Morell@icl-group.com

respectively, and compared with a K_0 control. Over the two-year experiment period, the treatments with polyhalite yielded 1.6 Mg ha^{-1} more the crop applied only with KCl, and 3.1 Mg ha^{-1} more than the K_0 control, differences that were particularly pronounced in the second, drier, 2020 season. Feed value parameters tended to increase under the polyhalite treatments, however, differences were not significant and require further investigation. Carbon footprints, calculated on the basis of dry matter production, were slightly lower in the polyhalite-applied crop, however, due to the higher production rates, carbon footprints per hectare were much higher in all fertilized treatments, compared to the control. An extended three to five year research period of alfalfa production would be necessary to finally assess these findings.

Keywords: Carbon footprint; feed value; *Medicago sativa*; Lucerne; MOP; Polysulphate; potassium; sulfur

Introduction

Alfalfa or Lucerne (*Medicago sativa*) is a deep-rooted, temperate, perennial pasture legume, which is a high protein feed for livestock. Global consumption of alfalfa hay was 197.8 million metric ton in 2018. Alfalfa consumption is expected to register a compound annual growth rate (CAGR) of 6.9% during 2019-2024. North America is the largest market for alfalfa hay, whereas China, UAE, and Saudi Arabia are major importers, mostly from the USA (Research and Markets, 2020). The USA and Europe are among the largest alfalfa producers in the world, accounting for around 7 million ha. In Europe, Spain and France are leading producers that also export dry alfalfa hay to countries not able to meet their own demand. In France, around 80% of the alfalfa is grown in the area east of Paris as a rainfed crop, producing three or four cuts each year, over a three-year period, and rotated with wheat. A steadily increasing part of the alfalfa production in France is shifting to organic farming systems.

Alfalfa produces high quality green feed for livestock. It has high energy – digestibility of 65-72% with a metabolisable energy of 8-11 MJ kg^{-1} DM – and a high protein content (12-24%). Alfalfa grows in areas receiving as little as 325 mm annual rainfall but also provides good summer production in areas with up to 700 mm rainfall. While the crop can quickly respond to significant summer rainfall (>10 mm), it requires 20-25 mm to produce substantial growth. Where suitable environmental conditions prevail, a rain-fed alfalfa pasture can produce 4-8 Mg DM ha^{-1} a year (Revell and Dolling, 2018). However, yields are highly sensitive to the current precipitation regime.

Alfalfa crops can fix 10-20 kg ha^{-1} of nitrogen (N) per tonne of dry matter produced, increasing soil N levels for subsequent crops. However, N fixation, and consequently, protein production and content, strongly depend on soil fertility. Alfalfa has a recommended pH range of 5.2-8.0, and is sensitive to soil acidity below pH ($CaCl_2$) of 4.8. On soils with low pH, the crop would benefit calcium-rich fertilizers. Phosphorus (P) is the nutrient most often required by alfalfa even though the uptake of other nutrients by the crop is much greater. Phosphorus is tied up in high pH soils, where it forms insoluble minerals with calcium. Transported to the roots by diffusion, a process that slows down in cool soils, P application is of particular importance during the cooler months of the year (Ottman, 2010).

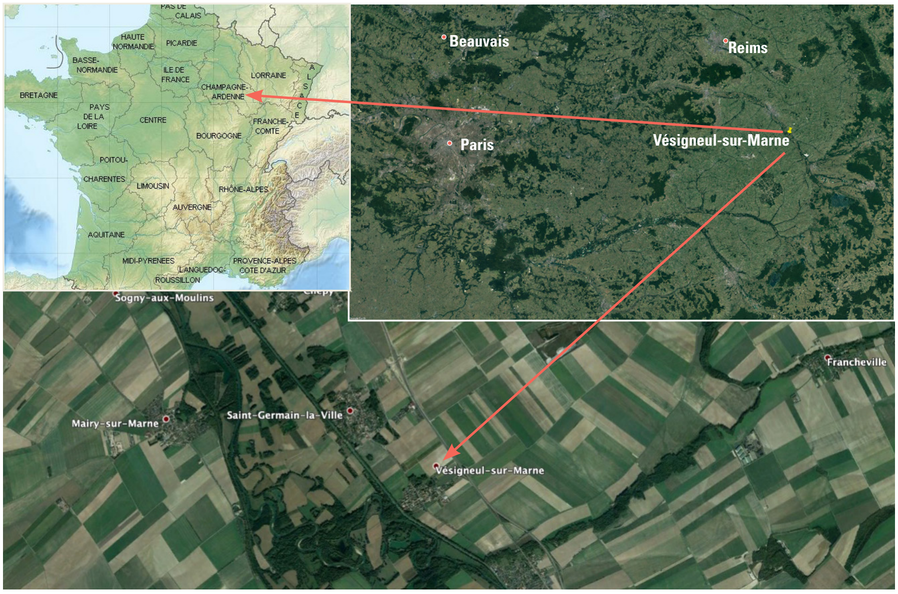
Potassium (K) fertilization is an important, though controversial, management aspect to consider in alfalfa. In rainfed production, the recommended soil K status is 100-200 mg kg^{-1}; an application dose of 20-40 kg K ha^{-1} is recommended for lower K status soils (Revell and Dolling, 2018). However, even on non-limiting K soils, K application may still have a positive effect on yield (Macolino *et al.*, 2013). For highly productive alfalfa (about 15 Mg ha^{-1}), a much higher dose of 300 kg ha^{-1} year^{-1} is often recommended. However, luxury consumption, with possible negative effects on forage nutritive value, have been found when K supply is too high (Lloveras *et al.*, 2012; Jungers *et al.*, 2019).

Alfalfa has high sulfur (S) requirement, estimated from 45-70 kg ha^{-1}. Sulfur is an important nutrient for alfalfa as a component of specific amino acids, lysine and cysteine, that are essential for protein metabolism. Therefore, S influences yield, protein content, stand density, and stand life of alfalfa. Sulfur supply is often missing or inadequate, leading to unbalanced nutrient supply to the crop. Yield and quality responses can be clearly observed in response to S fertilizer applications, when soil S levels are low (Michigan State University Extension, 2016). In addition, soil deficiency of secondary macronutrients, such as calcium (Ca) and magnesium (Mg), might significantly impair crop production and quality, in alfalfa, as well as in other crops (Kumar, 2011; Marschner, 2012). Thus, a balance between crop nutrient requirements and fertilizer supply should be reached to ensure high yield and quality.

The awareness of the environmental consequences of food production is steadily growing (Brankatschk and Finkbeiner, 2017; Peter *et al.*, 2017; Flachowsky *et al.*, 2018; Balogh and Jámbor, 2020; Panchasara *et al.*, 2021), focusing on the water and carbon footprints of various crops and products. While rainfed alfalfa displays a minor water footprints, the carbon footprint of this crop is more complex and is the subject of recent research (Druille *et al.*, 2017; Bacenetti *et al.*, 2018; Wagle *et al.*, 2019). Where fertilizer application is required, the nature and sources of the fertilizers used might significantly affect the crop's overall environmental impact (Chojnacka *et al.*, 2019). In this respect, natural fertilizers seem advantageous compared to chemically manufactured ones.

Polyhalite is a natural mineral which occurs in sedimentary marine evaporates and consists of a hydrated sulfate of K, Ca, and Mg with the formula: $K_2Ca_2Mg(SO_4)_4 \cdot 2(H_2O)$. The deposits found in Yorkshire, in the UK, typically consist of K_2O: 14%, SO_3: 48%, MgO: 6%, CaO: 17%. As a fertilizer providing four key plant nutrients – S, K, Mg, and Ca – polyhalite offers attractive solutions to crop nutrition. In addition, polyhalite is less water soluble than more conventional sources (Yermiyahu *et al.*, 2017; Yermiyahu *et al.*, 2019) and is, therefore, a suitable fertilizer to supply these four nutrients during rainy growing seasons. Polyhalite is available in its natural form as Polysulphate® and has been approved as an input for organic production systems in many countries. Due to its relatively low K content, fortification of polyhalite application with additional K sources, such as KCl (potassium chloride, also known as muriate of potash – MOP) should be considered according the K demands of the crop.

The objectives of the present study were to evaluate polyhalite, in combinations with KCl, as a K source for alfalfa, and to examine the response of both yield and quality to increasing proportions of polyhalite. Additionally, the carbon footprint of alfalfa was calculated, comparing the polyhalite and KCl treatments.



Map 1. Location of the experiment site in France. Sources: https://www.map-france.com/ and Google Earth.

Materials and methods

A field trial was established on second year alfalfa, in winter 2019 (GPS, latitude 48.884, longitude 4.476), Vésigneul-sur-Marne, France. Soil at the trial location was a calcareous soil (52% calcium carbonate), pH 8.2, with 2.2% soil organic carbon. Soil texture was silt loam, with 12% clay and 27% sand.

According to local guidelines, soil P content was low (61 mg P_2O_5 kg^{-1}), and K content high (431 mg K_2O kg^{-1}). Fertilization rates were established to supply 300 units of K_2O, following general potassium fertilization recommendations in the region (Circulaire 156, Coop de France Déshydratation, www.culture-luzerne.org/).

Four different treatments were established with combinations of 2 different sources of potassium, potassium chloride (potash), and polyhalite (as a powder and a granular product, 14% K_2O). The polyhalite also added magnesium, calcium and sulphur (Table 1). A control was established which received no additional nutrient supply.

The trial consisted of 3 replications, on a randomized complete block design. Individual plot size was 11.25 m by 2.5 m. Alfalfa productivity was assessed by harvesting the plot with a 1.5 m wide mower across the central part of the plots. Moisture content was assessed in each plot by oven drying under control conditions, and productivity referred to dry matter at 9% moisture content.

Precipitation has a significant influence on alfalfa productivity. The precipitation data was retrieved from NASA gridded weather data (https://power.larc.nasa.gov/data-access-viewer/).

Feed quality parameters were assessed from a mixture of samples from the 3 replicates. The nitrogen content and all other quality parameters were obtained using NIRS technology (Near Infra-Red Spectroscopy). The protein digestible in the intestine

Table 1. Fertilizer application and nutrient additions.

Treatment	Fertilizer rate		Nutrient rate			
	MOP (KCl)	Polyhalite	K_2O	MgO	SO_3	CaO
	kg ha^{-1}					
Control	0	0	0	0	0	0
KCl	500	0	300	0	0	0
200p	450	200 (granular)	300	12	96	32
405p	405	405 (granular)	300	24	194	65
800p	310	800 (powder)	300	48	384	128

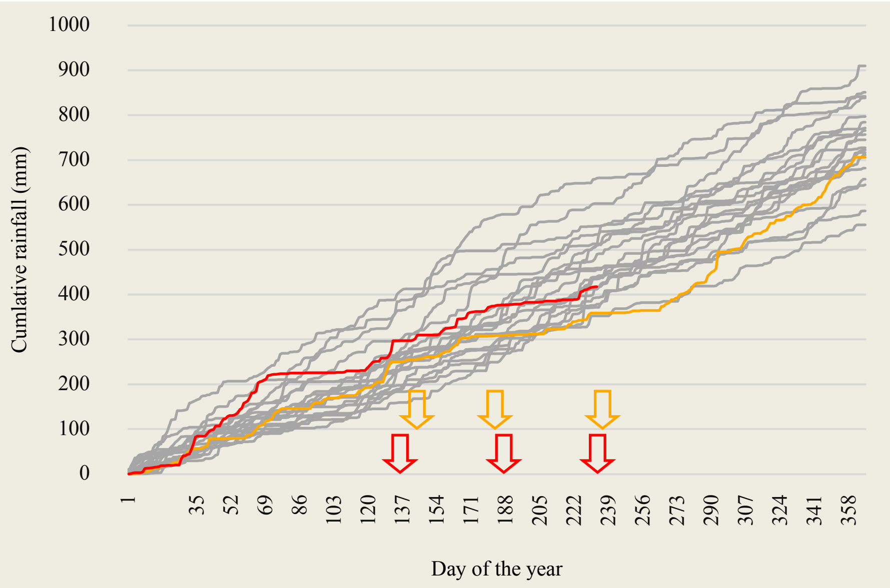


Fig. 1. Cumulative rainfall at the trial location (gridded data from POWER Data, NASA). Gray lines indicate cumulative rainfall in various years; Orange line indicates cumulative precipitation in 2019; red line indicates cumulative rainfall in 2020, until DOY 233, 20th of August (third and last cut). Arrows indicate the days the alfalfa was cut during the experiment (orange arrows for 2019, and red arrows for 2020).

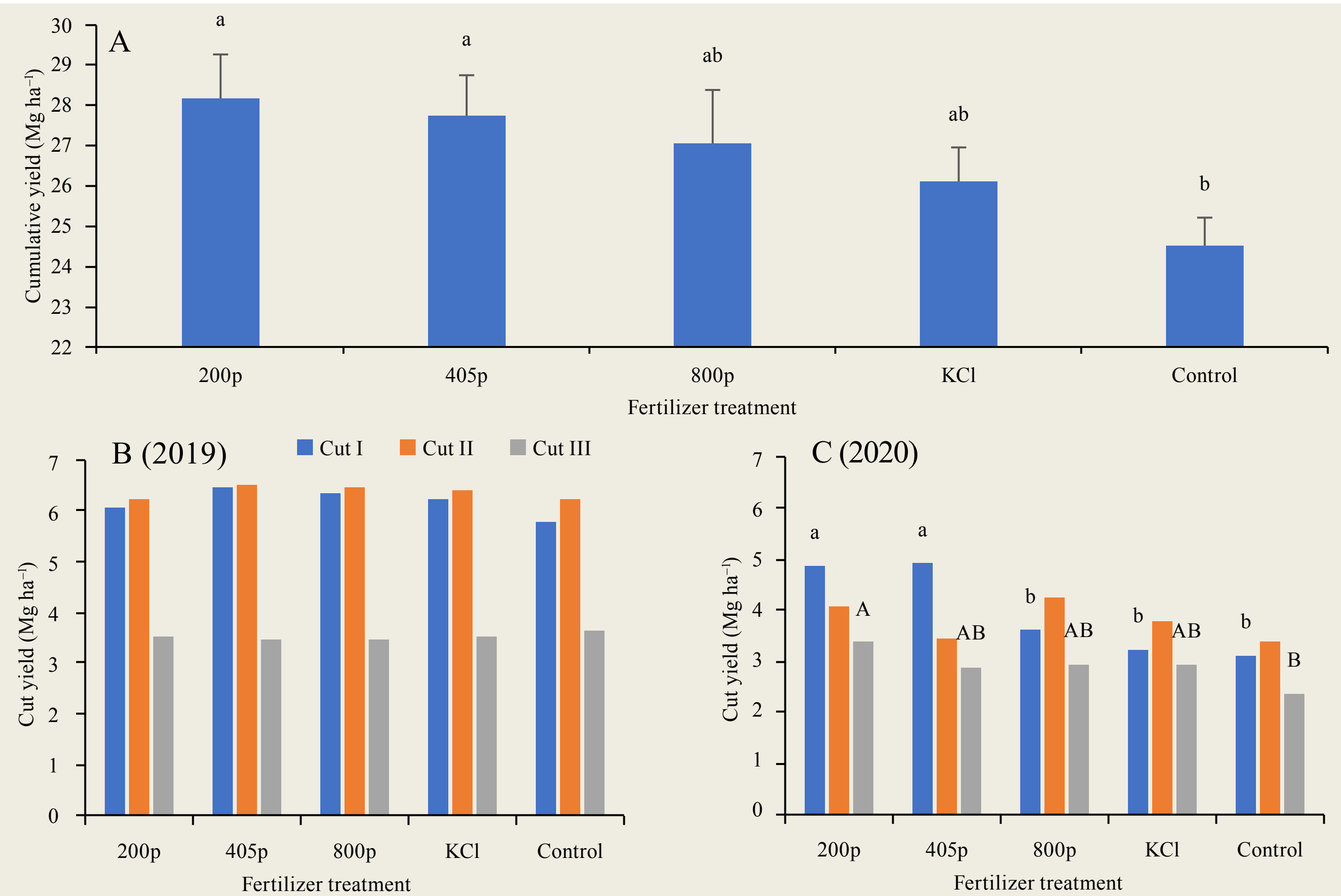


Fig. 2. Effects of the fertilizer treatments on the cumulative yield over the two successive growing seasons, 2019 and 2020 (A), and separately, on the yield of each cut during 2019 (B), and 2020 (C). For detailed treatment description refer to Table 1. Similar letters indicate no statistical differences between treatments at P>0.05.

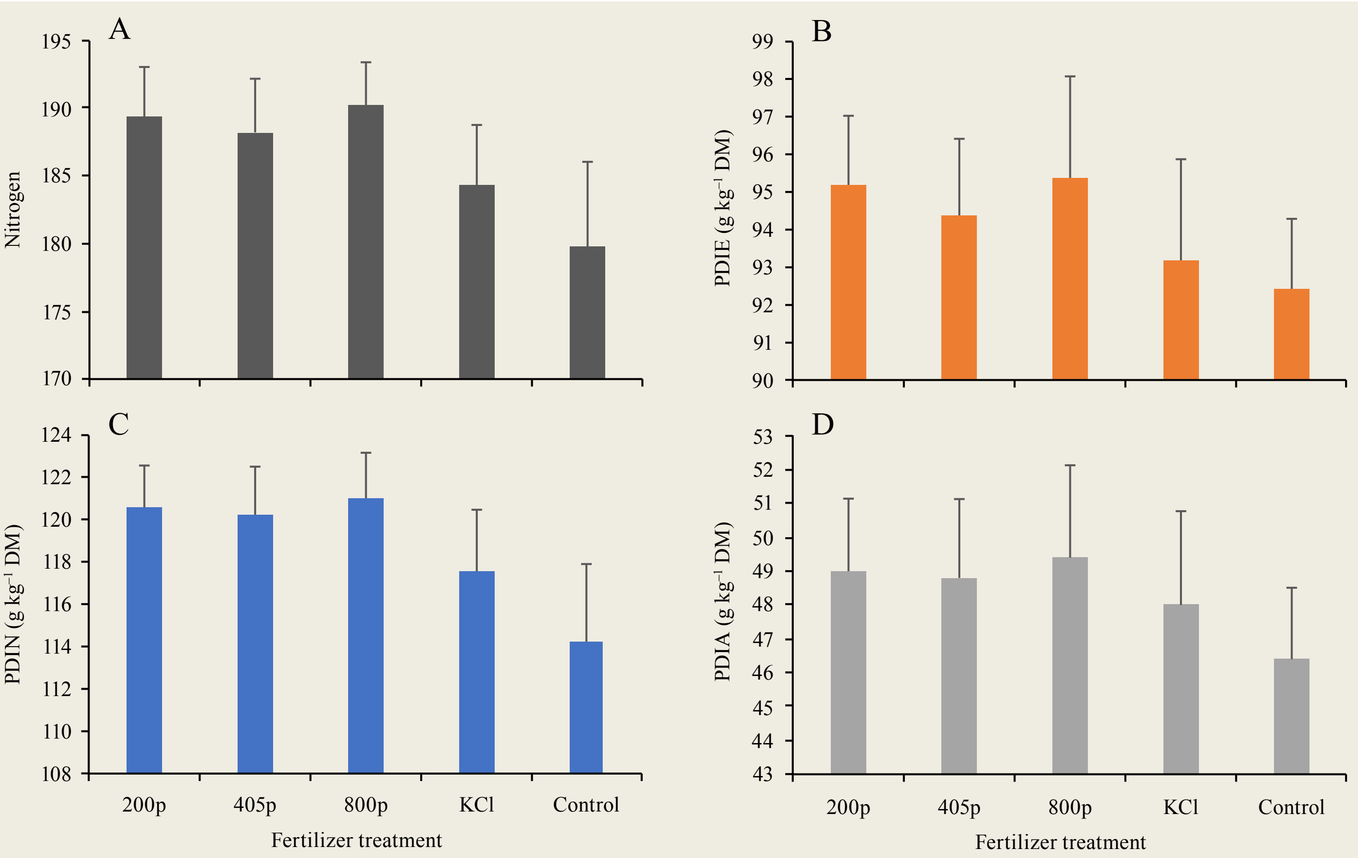


Fig. 3. Effects of the fertilizer treatments on the alfalfa quality parameters. Total protein content (A); PDIA – dietary protein undegraded in the rumen but actually digestible in the small intestine (B); PDIN – digestible protein in the intestine limited by nitrogen (C); PDIE – digestible protein in the intestine limited by energy (D). For detailed treatment description refer to Table 1.

system (PDI, after Vérité *et al.*, 1979; INRA, 2010) estimates the quantity of amino-N × 6.25 absorbed in the small intestine from the dietary protein which has escaped fermentation in the rumen, and the microbial protein arising from that fermentation. Two PDI values are ascribed to each feed: PDIN is calculated from both the degradable and non-degradable N contents; PDIE is calculated from both the rumen available energy and non-degradable N contents. Calculating the PDI value of a given diet, the PDIN and PDIE values of the different ingredients are summed separately, and the final PDI is the lower of the two values. Both PDIN and PDIE depend on PDIA, which expresses the non-degradable dietary protein in the rumen but truly digestible in the small intestine, as follows:

$$PDIN = PDIA + PDIMN$$
$$PDIE = PDIA + PDIME$$

Where PDIM is the microbial factual protein digestible in the small intestine. Each feed contributes to microbial protein synthesis both by the degradable N (PDIMN), and the available energy that it supplies to the rumen micro-organisms (PDIME).

Statistical analyses of yield were performed on a single factor analyses of variance for each of the six cuts. Statistical analyses of quality parameters were assessed comparing all 5 samples, as a sample of values for each treatment, on a single factor (Treatment) analysis of variance.

Finally, an assessment of the C footprint of each treatment was obtained with the Cool Farm Tool (https://coolfarmtool.org/), to assess the environmental impact of each strategy. The assessment of the carbon footprint of each of the strategies took into account the energy costs of the alfalfa drilling (1 operation), spraying (twice a year), baling (six operations, one for each cut), and where applicable, the energy cost of the fertilizer manufacturing and spreading (two applications).

Results and discussion

The mean cumulative production in 2019 was 16.12 Mg ha^{-1}, compared to 10.62 Mg ha^{-1} in 2020. The substantial difference between the two years may be attributed to differences in the precipitation regimes rather than to the cumulative precipitation, which was similar in 2019 and 2020, with a dry spell in both years from mid-July to the end of

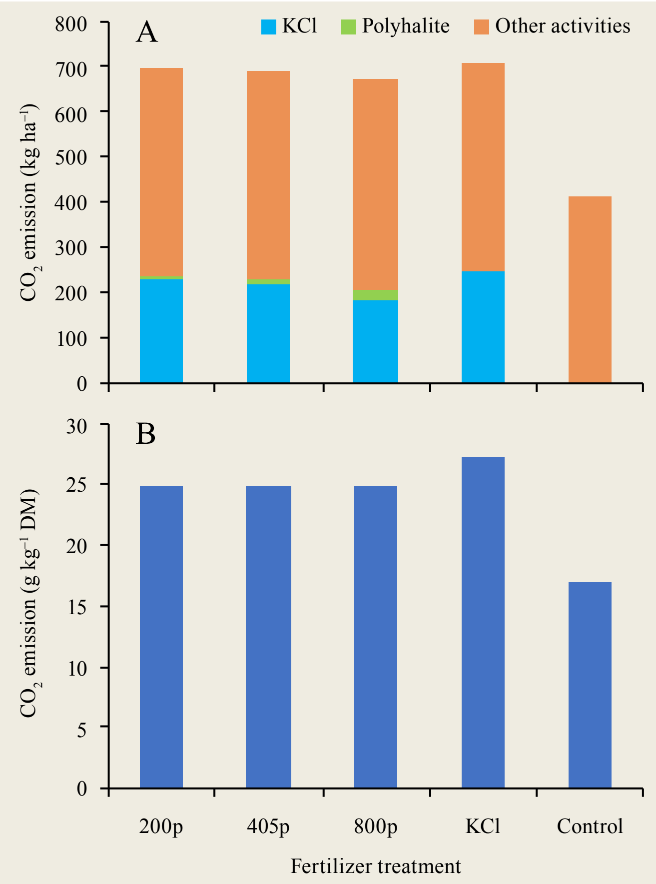


Fig. 4. Effects of fertilizer treatments on CO_2 emission rates associated with rainfed alfalfa production. Distribution of CO_2 emission due to KCl, polyhalite, and other operation activities, expressed as kg CO_2 ha^{-1} (A); Specific CO_2 emission (g CO_2e kg^{-1} DM), as affected by the fertilizer treatments (B). For detailed treatment description refer to Table 1.

August (Fig. 1). The lower productivity in 2020 can be associated to a dry spell during March and April (DOY, 62 to 120, Fig. 1), which negatively affected the productivity of the first cut.

In the first season, dry matter production was similar, with no significant differences between the treatments. The unfertilized control tended to have the lowest cumulative production, on average 0.5 Mg ha^{-1} lower than the fertilized alfalfa (Fig. 2B). In the second season, however, the differences among treatments were more pronounced, with significant differences in 2 out of the 3 cuts (Fig. 2C). Over the whole experiment period, the alfalfa fertilized with polyhalite yielded 1.6 Mg ha^{-1} more than the crop fertilized with MOP, and 3.1 Mg ha^{-1} more than the K_0 control (Fig. 2A).

Quality assessment was performed on a composite sample from each cut, without replicates, in order to identify trends. A clear trend was observed in all cuts – especially in the second year – with improvments in all the quality parameters of the polyhalite-applied (Fig. 3). Nevertheless, this consistent tendency over two successive years was not statistically significant. Alfalfa sensitivity to other limiting factors, such as drought, might have overridden some of the fertilizer effects. With a crop cycle duration of three to five years, these trends may become more significant through further examinations.

In the present study, the calculated CO_2 emissions (CO_2e) associated with alfalfa production were 416 and 710 kg ha^{-1} (Fig. 4A), or 17 and 27 g kg^{-1} DM (Fig. 4B), for the control and the MOP-applied treatments, respectively. The significantly higher yields of all fertilized treatments, compared to the unfertilized control, imposed higher CO_2e rates, 460-463 vs. 416 kg ha^{-1}, respectively (comparing only the emissions associated with the activities related to alfalfa production, and excluding emissions associatied with fertilizer production) (Fig. 4A). Of the alfalfa production activities, the major contribution to CO_2e was attributed to the baling operations, with a total of about 300 kg CO_2 ha^{-1}. When compared to other farming systems (e.g., irrigated alfalfa), or to other crops, these C footprints are considered low, largely due to the very low input intensity and energy cost of rainfed alfalfa field operations. Fertilizer manufacturing and transport were the second largest CO_2e contributor, ranging from 208–250 kg CO_2 ha^{-1} (Fig. 4A). In this sense, the low C footprint of polyhalite in contrast to KCl, 0.034 vs. 0.250 g CO_2 kg^{-1} product, respectively, may explain the slight increase in the estimated specific CO_2e of the KCl treatment compared to combined treatments (Fig. 4B).

Conclusions

Rainfed alfalfa production productivity and quality improved with K fertilizer application. Polyhalite, a natural mineral fertilizer containing K, Ca, Mg, and S, was used to partially replace KCl in supplying alfalfa K requirements, with the advantage of providing secondary macronutrients. Consequently, combined polyhalite and KCl application gave rise to significantly higher yields, and a tendency to improve hay quality parameters. In addition, being a natural mineral fertilizer, polyhalite slightly reduces the C footprint of the crop. An extended research period examining alfalfa production over three to five years would be necessary to fully assess the yield and quality over the whole crop cycle.

Acknowledgements

This study was funded by the International Potash Institute.

References

Bacenetti, J., D. Lovarelli, D. Tedesco, R. Pretolani, and V. Ferrante. 2018. Environmental Impact Assessment of Alfalfa (*Medicago sativa* L.) Hay Production. Science of The Total Environment 635:551-558.

Balogh, J.M., and A. Jámbor. 2020. The Environmental Impacts of Agricultural Trade: A Systematic Literature Review. Sustainability 12(3):1152.

Brankatschk, G., and M. Finkbeiner. 2017. Crop Rotations and Crop Residues are Relevant Parameters for Agricultural Carbon Footprints. Agronomy for Sustainable Development 37(6):1-14.

Chojnacka, K., Z. Kowalski, J. Kulczycka, A. Dmytryk, H. Górecki, B. Ligas, and M. Gramza. 2019. Carbon Footprint of Fertilizer Technologies. Journal of Environmental Management 231:962-967.

Druille, M., V. Deregibus, and M.F. Garbulsky. 2017. Controles Ambientales del Crecimiento de Alfalfa (*Medicago sativa* L.) a lo Largo de un Gradiente Climático y Edáfico. Agriscientia 34(2):13-23.

Fischer, A., N.C. Friggens, D.P. Berry, and P. Faverdin. 2018. Isolating the Cow-Specific Part of Residual Energy Intake in Lactating Dairy Cows Using Random Regressions. Animal 12(7):1396-1404.

Flachowsky, G., U. Meyer, and K.H. Südekum. 2018. Resource Inputs and Land, Water and Carbon Footprints from the Production of Edible Protein of Animal Origin. Archives Animal Breeding 61(1):17-36.

Institut National de la Recherche Agronomique (INRA). 2010. Alimentation des Bovins, Ovins et Caprins. Besoins des Animaux – Valeurs des Aliments: Tables Inra 2007 mise à jour 2010. Editions Quae, Versailles, France.

Jungers, J.M., D.E. Kaiser, J.F.S. Lamb, J.A. Lamb, R.L. Noland, D.A. Samac, M.S. Wells, and C.C. Sheaffer. 2019. Potassium Fertilization Affects Alfalfa Forage Yield, Nutritive Value, Root Traits, and Persistence. Agronomy Journal 111(6):2843-2852.

Kumar, S. 2011. Biotechnological Advancements in Alfalfa Improvement. Journal of Applied Genetics 52(2):111-124.

Lloveras, J., C. Chocarro, L. Torres, D. Viladrich, R. Costafreda, and F. Santiveri. 2012. Alfalfa Yield Components and Soil Potassium Depletion as Affected by Potassium Fertilization. Agronomy Journal 104(3):729-734.

Macolino, S., L.M. Lauriault, F. Rimi, and U. Ziliotto. 2013. Phosphorus and Potassium Fertilizer Effects on Alfalfa and Soil in a Non-Limited Soil. Agronomy Journal 105(6):1613-1618.

Marschner, H. 2012. Marschner's Mineral Nutrition of Higher Plants. 3rd Edition, Academic Press, Elsevier.

Michigan State University Extension. 2016. Michigan Alfalfa Tissue Test Survey Provides Fertility Snap-Shot. www.canr.msu.edu

Ottman, M. 2010. Alfalfa Nutrient Requirements, Deficiency Symptoms and Fertilizer Application. UC Cooperative Extension, Plant Sciences Department, University of California. California. https://alfalfa.ucdavis.edu/+symposium/2010/files/talks/CAS20_OttmanAlfalfaFertilizer.pdf

Panchasara, H., N.H. Samrat, and N. Islam. 2021. Greenhouse Gas Emissions Trends and Mitigation Measures in Australian Agriculture Sector—A Review. Agriculture 11(2):85.

Peter, C., K. Helming, and C. Nendel. 2017. Do Greenhouse Gas Emission Calculations from Energy Crop Cultivation Reflect Actual Agricultural Management Practices?–A Review of Carbon Footprint Calculators. Renewable and Sustainable Energy Reviews 67:461-476.

Research and Markets. 2020. Alfalfa Hay Market – Growth, Trends, and Forecast (2020-2025). www.researchandmarkets.com/reports/4520188/alfalfa-hay-market-growth-trends-and-forecast#rela0-4663667.

Revell, C.,and P. Dolling. 2018. Lucerne – the Plant and its Establishment. www.agric.wa.gov.au/pasture-establishment/lucerne-plant-and-its-establishment

Vérité, R., M. Journet, and R. Jarrige. 1979. A New System for the Protein Feeding of Ruminants: the PDI System. Livest. Prod. Sci. 6:349-367.

Wagle, P., P.H. Gowda, and B.K. Northup. 2019. Annual Dynamics of Carbon Dioxide Fluxes Over a Rainfed Alfalfa Field in the US Southern Great Plains. Agricultural and Forest Meteorology 265:208-217.

Yermiyahu, U., I. Zipori, I. Faingold, L. Yusopov, N. Faust, and A. Bar-Tal. 2017. Polyhalite as a Multi Nutrient Fertilizer – Potassium, Magnesium, Calcium and Sulfate. Israel Journal of Plant Sciences 64:145–157.

Yermiyahu, U., I. Zipori, C. Omer, and Y. Beer, 2019. Solubility of Granular Polyhalite under Laboratory and Field Conditions. International Potash Institute (IPI) *e-ifc* 58:3-9.

The paper "Polyhalite Enhances Alfalfa Production, Quality, and Environmental Footprints – Short News from Reims, France" also appears on the IPI website.