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A farm-scale sustainability assessment of the anaerobic digestate application methods

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ABSTRACT

Digestate is the anaerobic digestion by-product that can be used as an organic fertilizer, but some agronomic and environmental concerns still hinder its application on land. This study aims to evaluate the agronomic performances (i.e., silage maize dry yield, protein content, and N uptake) and environmental sustainability of solid and liquid digestate fraction application in a field experiment involving two farms with different textures covering about 47 ha in North Italy. The best available distribution methods included mineral fertilizer (MF), mineral fertilizer in variable rate application (VRA) (VRA-MF), liquid digestate with a nitrification inhibitor (LD+), liquid digestate in VRA (VRA-LD), liquid digestate with a nitrification inhibitor in VRA (VRA-LD+), and solid digestate (SD) and were applied to silage maize (*Zea mays* L.) in 2019 and 2020 cropping seasons. Results showed that both digestate fractions gave satisfying agronomic performances (i.e., dry biomass > 13 t ha^{-1} and protein content > 6.8%), comparable to those of mineral fertilizers, irrespective of soil type and application techniques. On the contrary, system sustainability investigated with a spatial evaluation of nitrogen use efficiency (NUE) revealed a strong interaction between NUE and soil texture. Indeed, in fine-textured soil only the adoption of both VRA and the nitrification inhibitor allowed the liquid digestate to reach a NUE between 50% and 90% while SD exhibited poor NUE (e.g., < 50%). In conclusion, liquid digestate fraction might be an effective substitute for mineral fertilizers in silty soils meeting also environmental criteria when VRA or nitrification inhibitors are applied. Contrarily, longer-term experiments are requested to evaluate SD fraction sustainability.

1. Introduction

In recent years, worldwide there is a pushing need to move from the current economic model, based on the linear consumption of energy and matter, to a circular economic model which is based on the recovery and revalorization of wastes through recycling and re-use (Gregson et al., 2015). The transition toward a circular economy will be strategic in the next future to reduce the over-exploitation of natural resources and minimize the environmental impacts of human activities (OECD, 2018; UNEP, 2018). In these circumstances, biogas plants are considered to be a convenient energy source for carbon-free electricity production since no or very little amount of fossil fuels is employed. A recent study by Tsachidou et al. (2018) estimated that if biogas plants would be implemented on a global scale, the gross greenhouse gas emissions could be reduced by 10%.

Anaerobic digestate (AD) is the anaerobic digestion by-product that is produced at a rate of 180 million tonnes per year in the EU28 (European Commission, 2019). Depending on the feedstock sources, AD might contain 2–7 kg N t^{-1} therefore it can be used as an organic fertilizer. Indeed, the use of alternatives (e.g., AD) to mineral fertilizers may be a key factor in reducing fossil fuel dependency which, in turn, plays a big role in reaching sustainable development goals (IFA, 2020;

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Table 1
Soil profile characteristics at Farm 1 and 2.

Characteristic	Unit	Farm 1			Farm 2			
		0–0.5 m	0.5–0.9 m	0.9–1.5 m	0–0.5 m	0.5–0.7 m	0.7–1.0 m	1.0–1.5 m
		Ap	Bkg	Ckg	Ap	EB	Bt	C
Sand	g 100 g^{-1}	10	10	0	65	63	72	85
Silt	g 100 g^{-1}	46	45	64	24	25	11	11
Clay	g 100 g^{-1}	44	45	36	11	12	17	4
Bulk density	g cm^{-3}	1.51	1.58	1.57	1.41	-	1.46	1.45
pH		8.2	8.9	8.8	6.7	7.8	8	8.7
Calcium carbonate	g 100 g^{-1}	2	50	32	0	0	0	28
Organic carbon	g 100 g^{-1}	1.53	0.64	0.26	1.02	0.89	0.38	0.26
Total nitrogen	g kg^{-1}	1.30	0.50	< 0.50	0.87	0.71	< 0.50	< 0.50

Ladha et al., 2020). Satisfying agronomic performances are commonly reported when AD is applied in cereals, root, and forage crops (Chantigny et al., 2008; Riva et al., 2016; Walsh et al., 2012). The AD is usually separated into two fractions, i.e., liquid and solid, the former retaining the greater part of ammonia-Nitrogen (N) (NH_4^+-N) while the latter the organic matter and organic matter-derived N (Möller and Müller, 2012). As for other solid organic fertilizers, the solid AD fraction is commonly applied to the land by surface broadcast before its incorporation into the soil through tillage to reduce nutrient losses (Crolla et al., 2013). Conversely, the liquid fraction can be directly injected into the soil thus minimizing odor and N emissions into the atmosphere (Verdi et al., 2018; Zilio et al., 2021). Several environmental drawbacks may arise from unbalanced AD application, such as nitrate (NO_3^-) leaching and atmospheric ammonia (NH_3), and nitrous oxide (N_2O) emissions (Cameron et al., 2013; Delgado, 2002; Zilio et al., 2021).

Another important issue related to digestate application on land is the determination of the application dose. The classical Economic Optimum Rate approach, often used for mineral fertilizers, maximizes the farmers' financial returns but does not consider the environmental pollution risk (Basso et al., 2011). Consequently, many authors have proposed several methods to optimize fertilizer N application rates also considering the environmental protection goal. For example, two proposed methods involved the use of plant available soil water content (Basso et al., 2011) or Decision Support System for Agrotechnology Transfer (DSSAT) model (Cammarano et al., 2021) but both approaches require detailed information. Alternative criteria should be followed for identifying the optimum digestate rate. Indeed, digestate is a zero-cost by-product whose use as a fertilizer surrogate is restricted by possible side effects on the environment. Grillo et al. (2021) recently proposed the adoption of an agro-environmental sustainability index (AESI), defined as the product between dry yield and nitrogen use efficiency (NUE), as a synthetic and rapid tool to define the optimal N rates of by-products (e.g., digestate) combining agronomic and environmental sustainability and, thus providing new insight into the circular economy through the better utilization of existent resources as digestate.

Uniform rate application represents the standard fertilization practice, being easier to manage for farmers on a large-scale field (Scharf et al., 2005). Moreover, the real crop N demand is usually difficult to define due to spatial and temporal variability, and over-application might often result in the fastest solution to fully exploit crop yield potential. Nevertheless, these practices lead to a mismatch between N inputs and crop N needs (Khosla and Shaver, 2001) which may negatively impact N use efficiency with the consequent environmental and economic drawbacks (Basso et al., 2016). During the last decades, N site-specific management (e.g., variable-rate application "VRA") has been demonstrated to be a suitable tool for increasing the N efficiency by maintaining, at the same time, crop production (Basso et al., 2013; Robertson et al., 2012) and decreasing the intra-field yield variability (Schillaci et al., 2021). Moreover, Morari et al. (2018) highlighted how VRA might partially counteract the effect of meteorological variability across different cropping seasons. A 10-yr study showed as VRA based on both prescription maps and real-time sensing allowed to decrease N input up to 32% and increased yield of 40% (Schillaci et al., 2020). However, recently Fassa et al. (2022) downplayed the VRA advantages of N saving which was estimated being only about 12% with respect to uniform management. To the best of our knowledge, only one attempt dealing with the VRA application of digestate exists in the literature. Indeed, Zilio et al. (2021) recently studied VRA liquid digestate application on maize concluding that its correct management might reduce NH_3 and odor emissions compared to synthetic fertilizers. Nevertheless, there is a gap in knowledge of the potential benefits of VRA digestate application in terms of crop yield and NUE. Moreover, the interaction between VRA digestate application with other NUE-increasing technics, such as nitrification inhibitors, was not so far investigated.

For these reasons, this study aimed to evaluate in real farm conditions, i) the crop performances (e.g., dry yield and N uptake) of silage maize in response to VRA (liquid AD fraction and mineral fertilizers) or uniform fertilizer application (liquid and solid AD fractions and mineral fertilizer), ii) their NUE and, iii) their agro-environmental sustainability by considering the best available distribution methods. Our starting hypotheses are that i) AD fractions might represent a reliable alternative to mineral fertilizers, allowing to achieve crop yield comparable to the standard mineral fertilizer application method, ii) liquid AD fraction might exhibit NUE comparable to mineral fertilizer one, being higher compared with solid AD fraction and, iii) liquid AD fraction applied according to the VRA method, integrated with nitrification inhibitors might achieve sustainable use of N in agriculture and food systems.

2. Materials and methods

2.1. Experimental sites description

A field experiment involving two farms in the Veneto region (North-Eastern Italy) was conducted in 2019–2020. Farm 1 (F1) is located in Mira (Venice) (45°24.253'N; 12°9.982'E) on a lagoon plain, which formerly originated as a transition area between the alluvial plain and the sea. The area developed as a marshland that was later reclaimed. F1 lies below sea level (−1 m a.s.l.), and agricultural activity is made possible by controlling the depth of the water table by subsurface drainage systems. Soils are also highly decarbonated due to the ancient age of the alluvial surface underneath the surface horizon with texture classes ranging between silty clay and silty clay loam (Table 1). These are classified as Endogleyic Vertic Calcisols (Epiclayic and Endosiltic) or Calcic Gleysols (Calcaric, Hypereutric, and Orthosiltic) (WRB, 2006). Farm 2 (F2) is located in Salizzole (Verona) (45°14.870'N; 11°4.523'E) on an alluvial plain originating from relatively coarse Adige river deposits, which originate soil types with sandy loam to loam surface texture classes. Soils are classified as Cutanic Luvisols (Hypereutric) with a reddish colored argic horizon due to illuvial clay accumulation or Haplic Cambisols (Hypereutric) (WRB, 2006). The organic carbon content is low (0.7–0.9%) and soils are mostly well-drained, due to coarse particle size presence (Table 1).

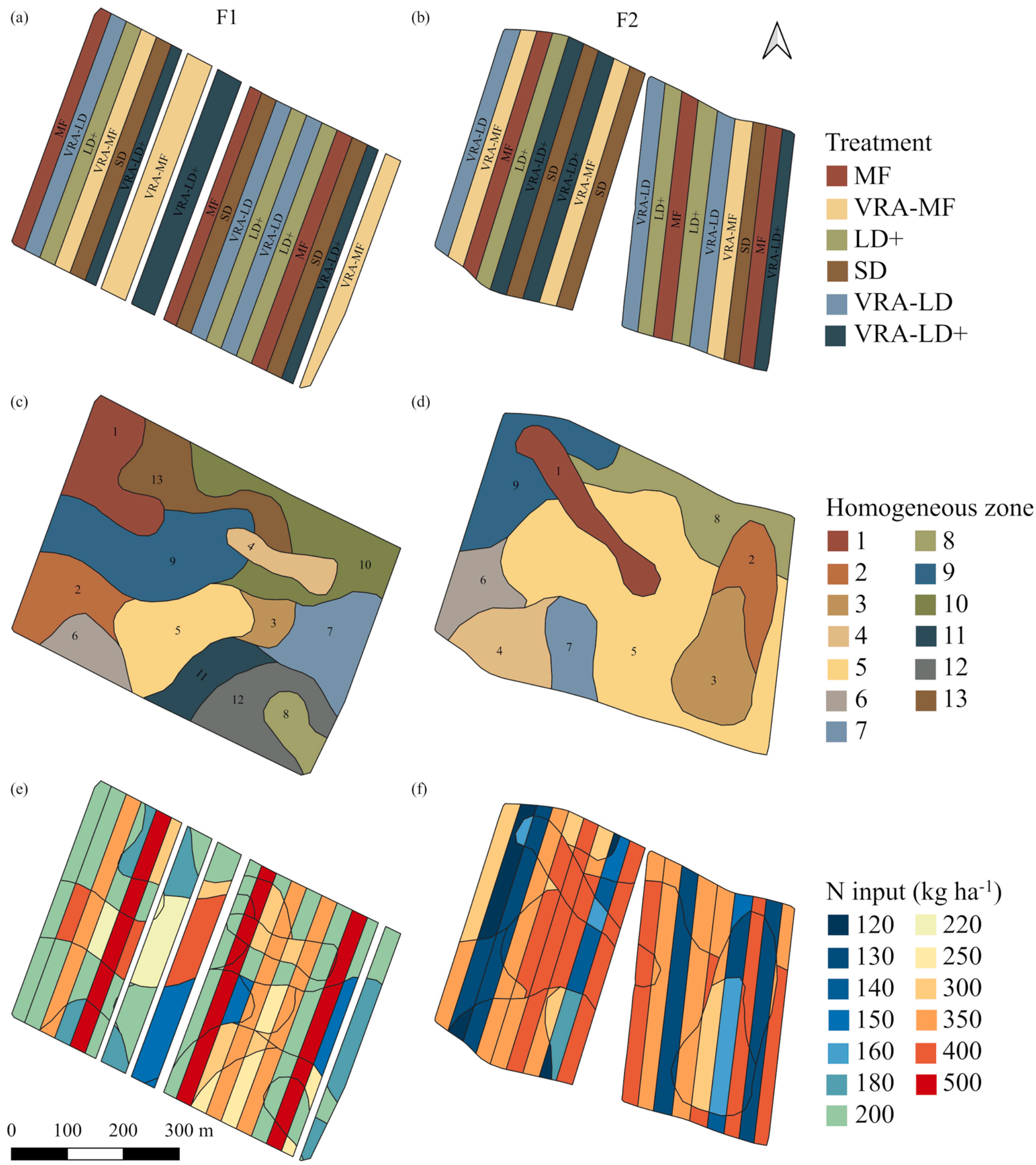

Fig. 1. Experimental design (a and b), soil homogeneous zones (c and d), and applied N rate (e and f) at F1 and F2.

The climate (2000–2019) is sub-humid, with an annual rainfall of 926 mm in F1 and 832 mm in F2. At both sites, rainfall is highest in the autumn and lowest in the winter, while the temperature rises from January (minimum average −0.5 °C and −0.4 °C, respectively) to July (maximum average: 29.7 °C and 31.1 °C, respectively). Yearly average temperatures are 13.6 °C (F1) and 14.1 °C (F2).

2.2. Experimental design

The field experiment is a complete randomized block design with three replicates allocated in 36 fields (6 treatments × 3 blocks × 2 farms) covering about 47 ha every year (1.3 ha per field, on average) (Fig. 1-a, b). The best available combination of techniques including mineral fertilizer (MF), mineral fertilizer applied with VRA (VRA-MF), liquid digestate added with a nitrification inhibitor, (N-Lock™, Corteva Agriscience, Wilmington, DE, USA) (LD+), liquid digestate applied with VRA (VRA-LD), liquid digestate added with a nitrification inhibitor and applied with VRA (VRA-LD+) and solid digestate (SD) was applied to silage maize (*Zea mays* L.) Dekalb DKC5530 (FAO class 400) in 2019 and 2020 cropping seasons in the same fields (Fig. 1-a,b). Maize was planted on 2nd/3rd (F1) or 3rd/4th week (F2) of June with a 75-cm inter row spacing and harvested in mid-September or the first half of October at both farms (Table 2). Maize was harvested at R4 dough and used as a substrate for biogas production.

The agronomic protocol differed between fertilizer types and employed a different combination of timing and method of fertilizer application—i.e., subsoiling followed by subsurface digestate injection and harrowing for liquid digestate fraction, amendment application and incorporation through 20 cm-plowing followed by harrowing for solid digestate fraction, and subsoiling followed by harrowing for mineral fertilizer. Crop fertilization consisted of one single application before tillage for the digestate fractions (VRA-LD, LD+, VRA-LD+, and SD

Table 2
Agronomic protocol according to fertilizer type and farm.

Operation	Mineral		Liquid digestate		Solid digestate	
	Farm 1	Farm 2	Farm 1	Farm 2	Farm 1	Farm 2
Subsoiling (0.2 m)	1st/2nd week of June	1st/2nd week of June	1st/2nd week of June	1st/2nd week of June	-	-
Disk harrowing (0.1 m)	1st/2nd week of June	2nd week of June	2nd/3rd week of June	2nd/3rd week of June	-	-
Harrowing (0.05 m)	-	-	2nd/3rd week of June	2nd/3rd week of June	-	-
Mouldboard ploughing (0.2 m)	-	-	-	-	2nd week of June	2nd week of June
Chisel ploughing (0.2 m)	-	-	-	-	3rd week of June	3rd week of June
Fertilization	1st: 2nd/3rd week of July 2nd: 3rd week of August	1st: 3rd week of July 2nd: 3rd week of August	2nd/3rd week of June	2nd/3rd week of June	2nd week of June	2nd week of June
Planting	2nd/3rd week of June	3rd/4th week of June	2nd/3rd week of June	3rd/4th week of June	2nd/3rd week of June	3rd/4th week of June
Pesticides application[a]	3rd week of August	3rd week of August	3rd week of August	3rd week of August	3rd week of August	3rd week of August
Harvesting	Mid of September/mid of October	1st/2nd week of October	Mid of September	1st/2nd week of October	Mid of September	1st/2nd week of October

-Operation not included in the agronomic protocol.
[a] Pesticide application for weeds and European corn borer (*Ostrinia nubilalis* (Hübner)) control

Table 3
Digestate characteristics during the experimentation at farm 1 (F1) and farm 2 (F2). DM: dry matter, VS: volatile solids; TN: total nitrogen; TP: total phosphorus; TK: total potassium.

	Site	DM	VS	TN	TP	TK
		g 100 g^{-1}	g 100 g^{-1}	g 100 g^{-1}	g 100 g^{-1}	g 100 g^{-1}
Liquid digestate	**F1**	9.9	7.30 (± 0.40)	0.76 (± 0.06)	0.20 (± 0.08)	0.52 (± 0.09)
	F2	6.1	4.10 (± 0.24)	0.64 (± 0.04)	0.11 (± 0.04)	0.36 (± 0.06)
Solid digestate	**F1**	23.8	21.20 (± 0.96)	0.69 (± 0.07)	0.23 (± 0.10)	0.61 (± 0.10)
	F2	21.1	18.10 (± 0.84)	0.70 (± 0.08)	0.22 (± 0.09)	0.40 ± (0.07)

treatments) and two side dressing applications for the MF (Table 2), using urea (50% application rate each). Irrigation was performed according to the crop water needs using rainger at F1 and emergency irrigation with a hose-reel sprinkler at F2. Irrigation was mostly based according to evaluation the visual plant symptoms. Pest management involved insecticide and fungicide treatments following crop requirements.

2.3. Digestate characteristics

The digestate used in this experiment was collected from two biogas plants located in the proximity of the experimental fields, both fed with energy crops (i.e., silage maize and silage winter wheat) and animal wastes (e.g., poultry manure and swine slurry in F1, cattle and swine slurry in F2). The biogas plants have a nominal power of 999 KWh; the reactors use thermophilic bacteria and work at a temperature between 52 °C and 56 °C with a residence time of 60 days. The obtained AD was then treated with a solid-liquid separation process to obtain solid (SD) and liquid (LD) fractions. LD was composed of 6.1–9.9 g 100 g^{-1} dry matter, 0.64–0.76% N, 0.11–0.20% P and 0.36–0.52% K while SD of 21.1–23.8 g 100 g^{-1} dry matter, 0.69–0.70% N, 0.22–0.23% P and 0.40–0.61% K (Table 3).

2.4. Management zones delineation and fertilizer application rate determination

Management Zones (MZs) were established using a mixed approach integrating a preliminary electrical conductivity (ECa) maps with traditional soil chemical analyses and soil classification maps (Nawar et al., 2017). The ECa was measured with Topsoil Mapper (Geoprospectors GmbH, Traiskirchen, Austria) in the 0–20, 0–40, 0–60, and 0–80 cm soil layers. At each farm, a provisional MZs map was obtained by applying the Fuzzy C-mean method (MZA 1.0.1, University of Missouri-Columbia, USA) to ECa maps (1 m length × 2 m wide resolution). A stratified random soil sampling was then performed in 54 positions per site to a depth of 30 cm, using MZs as strata. In order to characterize soil properties to a depth of 120–150 cm (drainage, water table depth, calcic or illuvial horizon presence, control section particle size) 30 pedological observations (28 auger holes and 2 soil profiles) were described in each site (Soil Survey Staff, 1993). Information about deep horizons allowed to evaluate soil functional properties, to differentiate MZs. Profile horizons and soil samples were analyzed for texture, bulk density, pH, electric conductivity, cation exchange capacity, soil organic carbon, total N, and available phosphorus (P). A total of 13 and 9 MZs (Fig. 1-c,d) at F1 and F2, respectively, were finally delineated by integrating the provisional MZs map with the high-detailed pedological map at scale 1:10.000, according to FAO standards (FAO, 1979) as further investigation of the already mapped area at scale 1:50.000, (ARPAV, 2005; Ragazzi and Zamarchi, 2008).

For each treatment and MZ, the optimal N fertilization rate was calculated by minimizing an Agro-Environmental Sustainability Index (AESI) based on 9-years Denitrification and Decomposition model (DNDC, version 9.3) (Li et al., 1992) simulations output, as reported in Grillo et al. (2021). The input parameters were daily weather data (e.g., temperature and rainfall), soil properties (e.g., soil density, texture, and initial SOC), land use (e.g., crop type and rotation system), and management practices (e.g., tillage, fertilization, irrigation, and crop residue management). Used soil properties were specific for each field in homogeneous treatment and for each MZ in VRA treatments. For each fertilizer type, the simulations were repeated at increasing N input from 50 to 500 kg N ha^{-1} with a 50 kg N ha^{-1} incremental step. Since digestate was not included in the DNDC model, its peculiar high mineral N content was represented as a combination of animal waste and urea. The proportions between the two components were defined in function of

Table 4
N input (kg N ha^{-1}) and surface (ha^{-1}) of the different homogeneous zones belonging to VRA treatments at F1 and F2.

	F1			F2		
	Zones	N input	Surface (ha)	Zones	N input	Surface (ha)
VRA-MF	1, 2, 5, 10, 12	200	1.70	1, 3	160	1.00
	6, 7, 8	180	1.28	2, 6	130	0.79
	9	210	1.08	4, 9	120	0.88
	13	180	0.69	5, 7	140	1.03
				8	150	0.35
VRA-LD	1, 2, 10	200	1.68	1, 5	400	1.40
	3	240	0.30	2, 6, 8	350	1.09
	4	350	0.26	3, 9	300	1.46
	5	150	0.22			
	7, 11, 13	300	0.66			
	9	400	0.31			
	12	250	0.57			
VRA-LD+	1, 2, 6, 10, 12	200	1.17	1, 5	400	5.83
	5, 7	150	1.23	2, 4, 6, 8	350	1.16
	8	180	0.18	7, 9	300	0.54
	9	400	0.99			
	13	300	0.38			

laboratory analysis. The model was run for each MZ belonging to VRA treatments while considering the average field soil properties for homogeneous application treatments for a total of 610 simulations. The ex-post model validation is reported in the supplementary materials Fig. S2-S6.

The optimal N application rates were then determined by maximizing AESI, defined as the product between the dry matter (yield) and the NUE, which combines agronomic and environmental criteria (Grillo et al., 2021). In both farms, the organic fertilizers (solid and liquid AD) rate complies with the Nitrate Directive (91/676/EEC) limit. The NUE was calculated as the ratio between the crop N uptake, calculated as the product between total above-ground dry biomass and its N concentration, and fertilizer N input (i.e., N application rate of each best available combination of techniques), according to the European Nitrogen Expert Panel (2015).

The optimal N fertilization rate was 200 kg N ha^{-1} at F1 and 130 kg N ha^{-1} at F2 in MF while varied in the 180–220 kg N ha^{-1} (F1) and 120–160 kg N ha^{-1} (F2) ranges in VRA-MF (Table 4). The N input in LD+ was 350 kg N ha^{-1} at both farms ranged being in 150–400 and 300–400 kg N ha^{-1} ranges at F1 and F2, respectively in VRA-LD and VRA-LD+ . The solid digestate was always applied at a 500 and 400 kg N ha^{-1} rate, for F1 and F2 respectively (Fig. 1-e,f). The simulated AESI was sensitive to the soil variability (i.e., MZ) showing higher values in finer soil with higher organic C content in both farms. However, AESI was more dominated by the treatment being in general higher in VRA-MF than VRA-LD and VRA-LD+ . The differences were particularly high at F1. For further details, please see the Table S1. The mineral fertilizer application was managed using a Bogballe M2W plus weight-controlled spreader (Bogballe S/A, Uldum, Denmark) equipped with a double-disk centrifugal distribution system and a control unit (Calibrator Zurf, Bogballe S/A, Uldum, Denmark). The solid digestate was uniformly distributed through a manure spreader. Liquid digestate was injected into the soil with a Hydro Trike XL (Vervaet, Biervliet, Netherlands) equipped with Vervaet SmartBox® that connected the different GPS systems to the section control on the injector and the calibrated NIR sensor (ITPhotonics, Fara Vicentino, Italy) on the machine. The equipment allowed to distribute the liquid digestate according to both

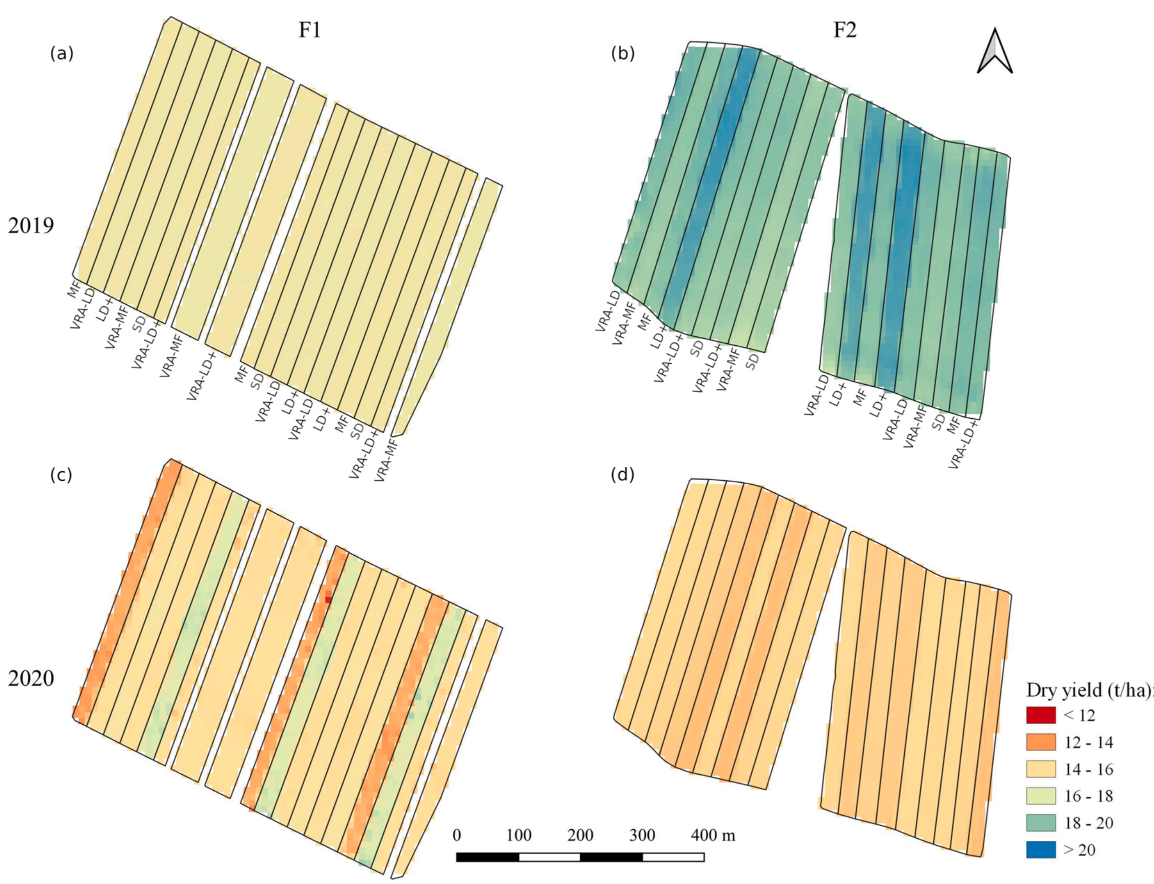

Fig. 2. Silage maize dry yield maps in 2019 (a and b) and 2020 (c and d) at F1 (a and c) and F2 (b and d).

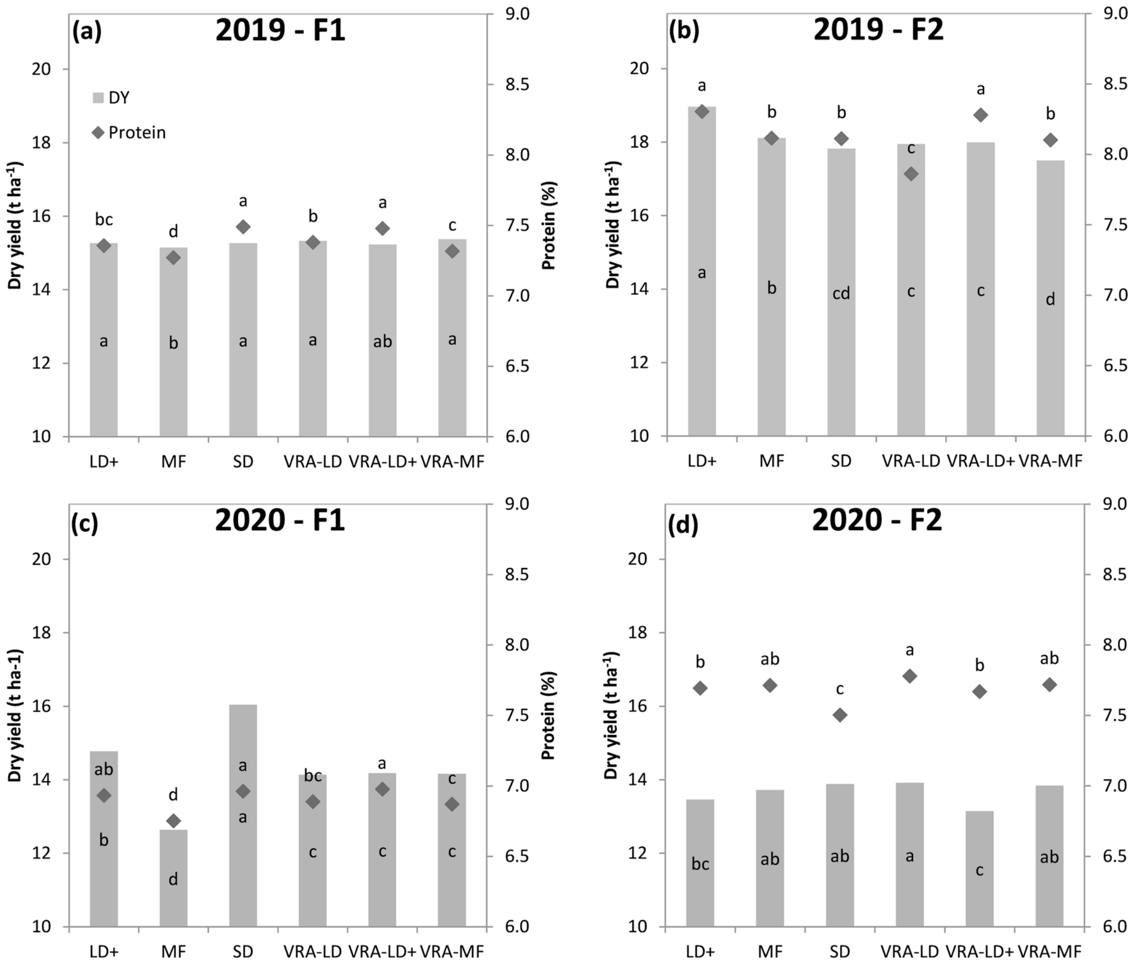

Fig. 3. Silage maize dry yield (bars) and protein content (points) in 2019 (a and b) and 2020 (c and d) at F1 (a and c) and F2 (b and d). Different letters indicate statistical difference according to Tukey posthoc test at $p < 0.05$.

prescription maps and liquid digestate composition thus being able to consider the heterogeneity of the medium.

2.5. Crop yield, crop N uptake and NUE

At maize R4 dough, yield data were recorded using a calibrated Cebis yield monitoring (accuracy ca. 5%) system mounted on a Claas Jaguar 990 and 980 forage harvesters (Claas, Harsewinkel, Germany). Similarly, crude protein content data were measured with a calibrated NIR spectrometer (ITPhotonics, Fara Vicentino, Italy) that was interfaced with a GPS. Crude protein was then converted in crop N uptake which was used to calculate NUE as the ratio between N uptake and N input (N applied with the different fertilizer), according to the EU Nitrogen Expert Panel (2015).

2.6. Statistical analysis

Statistical analysis was performed applying mixed effect models based on a restricted maximum likelihood estimation method Spatial data obtained from the forage harvester (i.e., maize yield and N uptake) was tested with a mixed model that accounts for a spatial variance-covariance structure testing the treatment (categorical variable) and ECa (continuous variable) as a fixed factor and blocks as random. The spatial correlation of residuals was modeled using the REPEATED statement of PROC MIXED (SAS, Cary, NC, USA). The post hoc pairwise comparison of least squares means was performed with the Tukey method to adjust for multiple comparisons at the significance level of $p < 0.05$. Statistical analysis was performed with SAS (SAS Institute Inc. Cary, NC, USA) version 5.1.

3. Results

3.1. Crop yield and protein content

Silage maize dry biomass ranged between 12.1 and 19.4 t ha^{-1} (Fig. 2). At F1, the 2019 DB exhibited values in the range of 15.1–15.5 t ha^{-1}, with slightly higher performances ($p < 0.05$) of VRA-MF, VRA-LD, SD, and LD+ (15.3 t ha^{-1}, on average) than MF (15.1 t ha^{-1}) (Fig. 3-a). At the same farm, a greater biomass variability was instead observed in 2020 (10.4–17.3 t ha^{-1}) (Fig. 2-c) where SD showed the highest yield (16.0 t ha^{-1}) being followed by LD+ (14.8 t ha^{-1}) while all VRA treatments (VRA-LD, VRA-LD+, and VRA-MF) showed lower production (14.2 t ha^{-1}, on average) (Fig. 3-c). An opposite trend was observed at F2 where 2019 was associated with greater yield variability (16.4–19.3 t ha^{-1} range) than 2020 (13.0–14.0 t ha^{-1} range) (Fig. 2-b,d). In 2019 the best performances were obtained in LD+ (19.0 t ha^{-1}) while lower yield was observed in VRA treatments and SD (Fig. 3-b). In 2020 the VRA-LD and VRA-LD+ gave the highest and the lowest yield, respectively (13.9 vs 13.2 t ha^{-1}) (Fig. 3-d).

The protein content ranged between 6.59% and 8.44%, slightly higher in 2020 than in 2019 at both farms (Fig. 3). At F1, consistent results were found across the studied years with SD resulting in the highest (7.49% in 2019 and 6.96% in 2020) and MF in the lowest protein content (7.27% in 2019 and 6.75% in 2020) (Fig. 3-a,c). Moreover, in

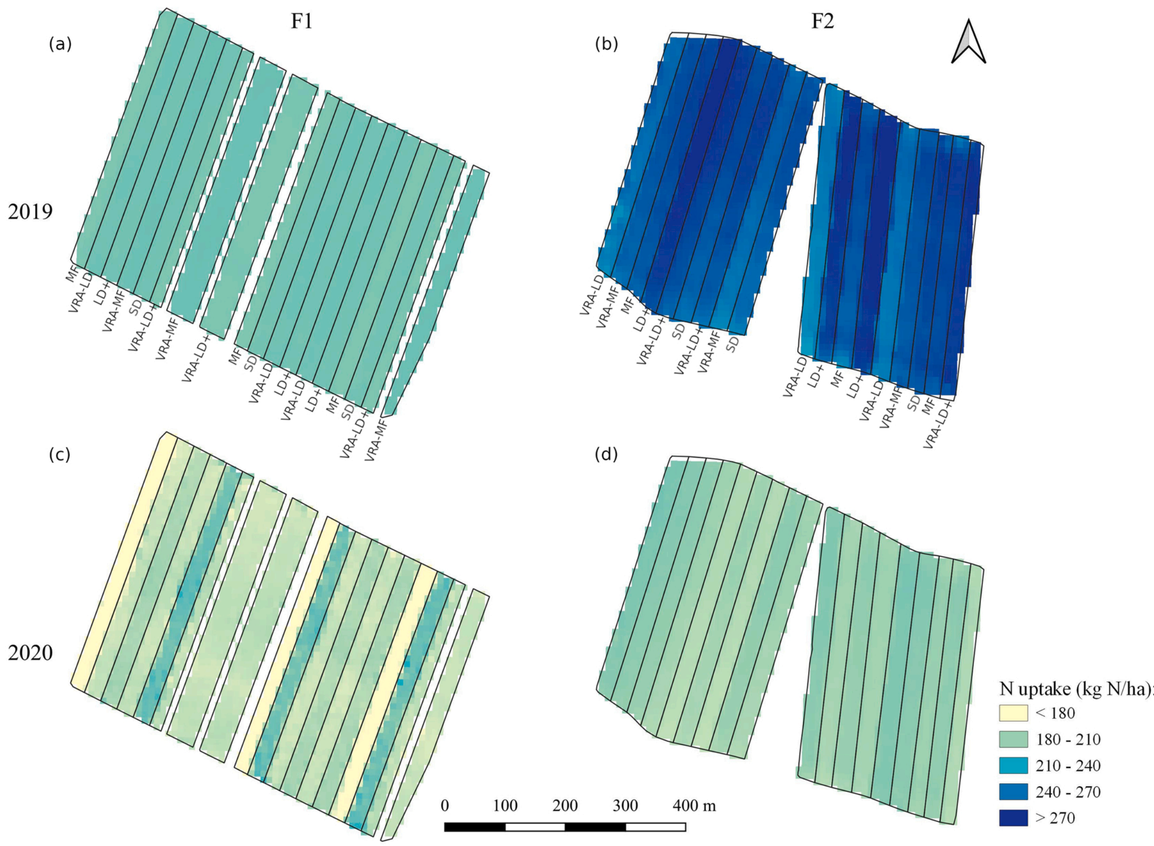

Fig. 4. Silage maize N uptake maps in 2019 (a and b) and 2020 (c and d) at F1 (a and c) and F2 (b and d).

both years the adoption of VRA increased the protein content of both mineral fertilizer and liquid digestate with nitrification inhibitors. Contrasting results were instead found at F2 where VRA-LD exhibited the lowest (7.86%) and highest (7.78%) performances in 2019 and 2020, respectively. At the same farm, the adoption of VRA showed protein content comparable to those of uniform application (Fig. 3-b,d).

3.2. Crop N uptake and nitrogen use efficiency

The silage maize N uptake ranged from a minimum of 189 kg N ha^{-1} at F2 2020 to a maximum of 215 kg N ha^{-1} at F2 2019 (Fig. 4). Similar to what was observed for dry biomass, N uptake showed low variation at F1 2019, being in the range of 186–191 kg N ha^{-1} (Fig. 4-a) with the treatments ranked as follows: VRA-MF > VRA-LD > LD+ and SD > VRA-LD+ > MF (Fig. 5-a). In 2020, the SD exhibited the greatest N uptake (191 kg N ha^{-1}) while lower values were associated with MF (146 kg N ha^{-1}) (Fig. 5-c). At F2 the adoption of VRA did not lead to greater N uptake for both mineral fertilizer (248 kg N ha^{-1} in VRA-MF vs 254 kg N ha^{-1} in MF) and liquid digestate with a nitrification inhibitor (261 kg N ha^{-1} in VRA-LD+ vs 269 kg N ha^{-1} in LD+) in 2019 (Fig. 5-b). In 2020, the best performance was reached in VRA-LD (185 kg N ha^{-1}) while the lowest in SD (172 kg N ha^{-1}) (Fig. 5-d).

The NUE varied from 37% to 100% at F1 meanwhile was in the 11–232% range at F2 (Fig. 6). At F1 consistent results were found across the studied years with the adoption of VRA increasing mineral fertilizer NUE from 93% (MF) to 98% (VRA-MF) in 2019 and from 0.72 (MF) to 86% (VRA-MF) in 2020 (Fig. 5-a). A similar trend was also observed for liquid digestate with nitrification inhibitor that increased from 55% (LD+) to 89% (VRA-LD+) in 2019 and from 52% (LD+) to 80% (VRA-LD+) in 2020 (Fig. 5-a,c). The lowest performance was recorded in SD in both years, being always < 40%. At F2, the treatments including mineral fertilizers gave always the best performances (NUE > 100) while organic fertilizers exhibited lower values, < 50% for SD and in the 90–50% range for liquid digestate, irrespective of application technique or presence/absence of nitrification inhibitor (Fig. 5-b,d). Contrarily to F1, the adoption of VRA did not improve NUE at F2 but was instead equal to or lower than uniform fertilizer application for both organic fertilizers (i.e., mineral and liquid digestate) and years (Fig. 5-b,d).

3.3. System sustainability

The minimum productivity threshold set at 120 kg N ha^{-1} was always reached irrespective of treatments, farm, or year (Figs. 7 and 8). The NUE > 50% was reached in all the F1 areas except in SD. At F2, the same criterion was always met in 2019 while covered only part of the liquid digestate treatments area, i.e., 9% in VRA-LD+ , 62% in LD+ , and 95% in VRA-LD in 2020 (Table 5). As opposite, NUE was < 90% in all the treatments including digestate fractions while was exceeded in MF and VRA-MF at both farms in 2020 and at F1 in 2019 (Figs. 7 and 8). The N surplus < 80 kg ha^{-1} was always met on 100% of the surface when mineral fertilizer was applied at both farms and years (Table 5). At F1, liquid digestate met the same criteria on more than half of the surface only when it was applied in VRA, irrespective of the application or not of a nitrification inhibitor (Table 5). On the contrary, at F2 liquid digestate met the threshold on a smaller surface (i.e., < 40%) only in 2019 while failed to meet the criterion in 2020. SD never complied with the N surplus < 80 kg ha^{-1} limit in both years.

Overall, the “sustainability zone” was fully reached in both years in more than half of the surface for VRA-LD and VRA-LD+ at F1 (Table 5). At the same farm, MF and VRA-MF were sustainable on 100% of the surface only in 2020. At F2, only liquid digestate treatments (i.e., LD+, VRA-LD, and VRA-LD+) partially (i.e., from 15% to 37% of the surface) reached the “sustainability zone” in 2019 (Fig. 7) while in 2020 no treatment met the overall criteria for a significant area (> 0.5%) (Fig. 8

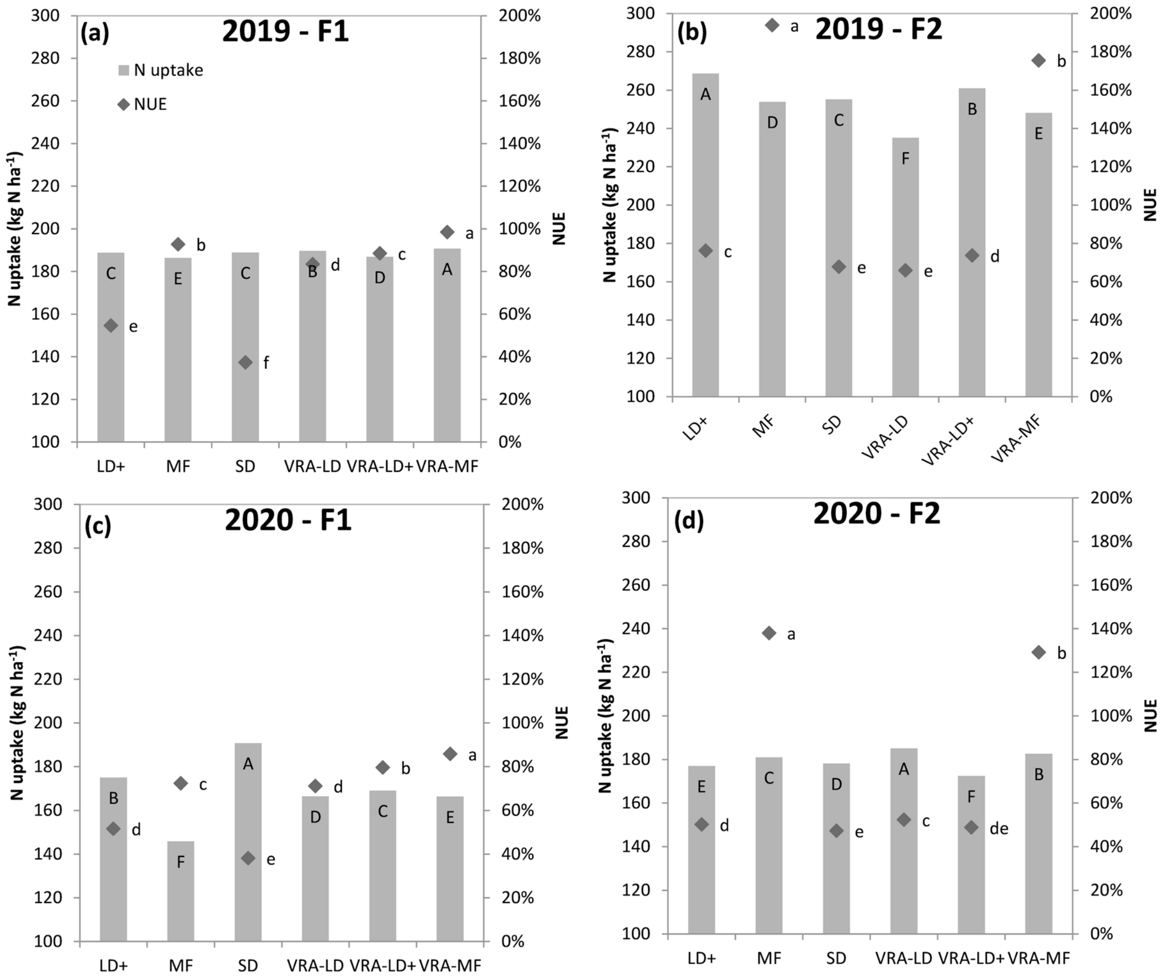

Fig. 5. Silage maize N uptake (bars) and nitrogen use efficiency "NUE" (points) in 2019 (a and b) and 2020 (c and d) at F1 (a and c) and F2 (b and d). Different letters indicate statistical difference according to Tukey posthoc test at $p < 0.05$.

and Table 5).

The AESI criteria as measured at harvesting reflected the same trends of DNDC-derived indices. Indeed, VRA-MF AESI (13.7 at F1 and 24.3 t ha^{-1} at F2, on average) was greater than VRA-LD (11.4 at F1 and 9.7 t ha^{-1} at F2, on average) and VRA-LD+ (12.4 at F1 and 9.8 t ha^{-1} at F2, on average) at both farms. However, the absolute AESI values were different than estimated by DNDC with higher value in F1 treatments including LD due to a higher observed NUE. A greater intra-treatment variability was then observed at F2 compared with F1 but without being any treatment significantly affected by MZ. For further details please see the Table S2.

4. Discussion

In this study, we evaluated the best available distribution methods including the application of liquid and solid digestate fractions, optimized accordingly to agronomic and environmental criteria. The AD-based methods led to crop performances (e.g., dry biomass and protein content) consistently comparable to those of the mineral fertilizer at both farms. Despite some statistical differences reported, all the treatments gave satisfying results –i.e., dry biomass > 13 t ha^{-1} and protein content > 6.8%, irrespective of soil type. Nevertheless, the application of the nitrification inhibitor does not lead to improved crop performance. It is worth noting that nitrification inhibitors are most effective in systems with low-N availability (Lata et al., 2004; Subbarao et al., 2007) while in this study the treatments with nitrification inhibitor (i.e., LD+ and VRA-LD+) involved a non-limiting N application rate being in the 150–400 kg N ha^{-1} range.

The digestate good performances were evidenced at both F1 and F2 characterized by a finer and coarser texture, respectively. Contrarily, Robles-Aguilar et al. (2019) found that digestate might be more beneficial on coarse soils due to the lower fertility of the original substrate. Promising results were previously reported by Sigurnjak et al. (2017) who suggested that the liquid digestate fraction may substitute synthetic N fertilizers without any silage maize yield losses. The same authors concluded that the nutrient variability, N first, will be one of the greatest challenges for the future utilization of bio-based fertilizers (e.g., digestate). In the present study, the application of liquid digestate in VRA showed to be one solution to cope with the soil spatial variability and digestate heterogeneous composition, at the same time, allowing to increase the NUE. Despite, to the best of our knowledge, no attempts are available in the literature on the efficiency of VRA liquid digestate, these findings might confirm what was previously observed for similar organic fertilizers (e.g., animal slurry). For example, Schellberg and Lock (2009) highlighted how the site-specific slurry application has the potential to reduce nutrient surplus and, in turn, the loss into the environment in both agricultural fields and grassland. This goal was further confirmed in F1 where N input was reduced from 350 kg N ha^{-1} in uniform distribution to 243–249 kg N ha^{-1} in VRA-LD+ and VRA-LD, respectively. The VRA allowed exploiting the spatial interaction between soil characteristics, crop growth and fertilizer input, resulting in N input ranging from 150 to 400 kg N ha^{-1}. Poor results were instead obtained in F2 where the average N input was not reduced by VRA and the N-VRA ranged from 300 to 400 kg N ha^{-1}.

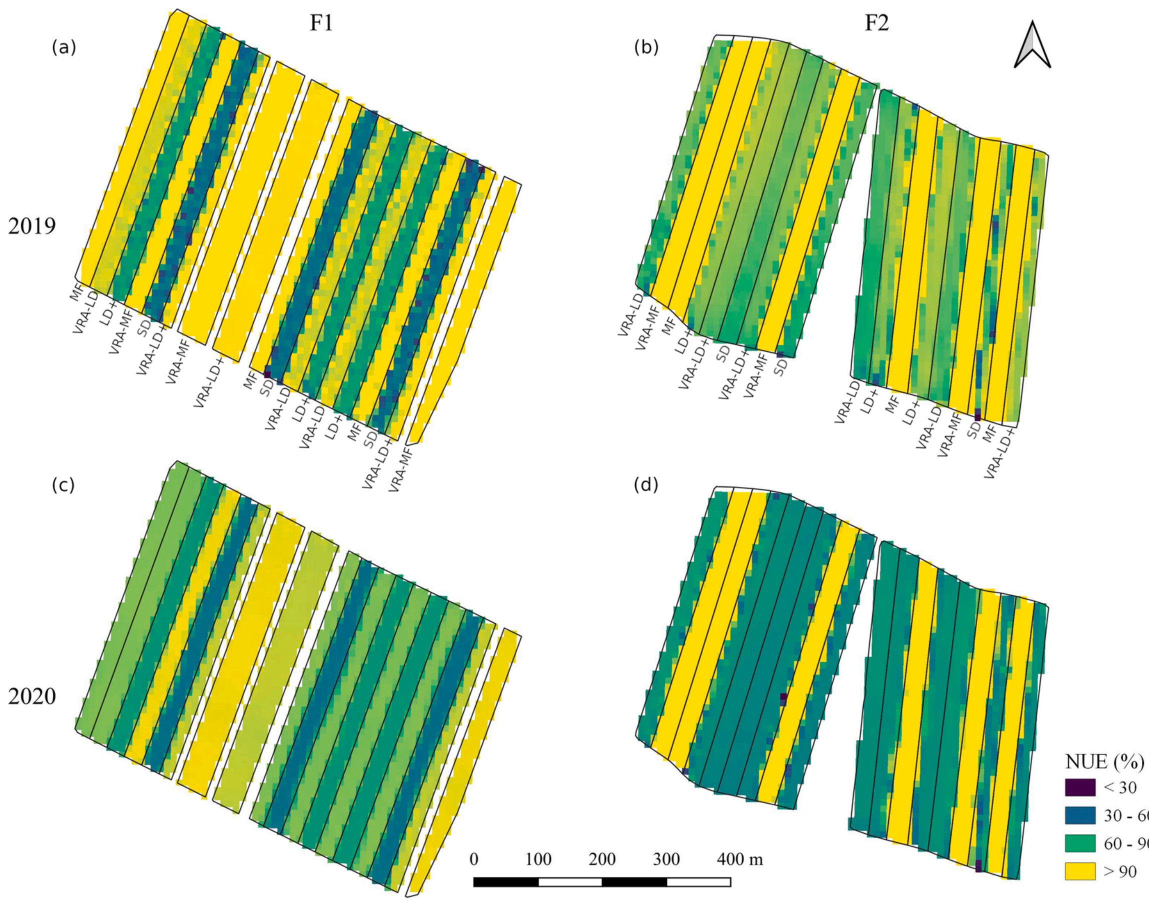

Fig. 6. Silage maize nitrogen use efficiency “NUE” maps in 2019 (a and b) and 2020 (c and d) at F1 (a and c) and F2 (b and d).

Solid AD fraction is usually recognized as a good amendment rather than fertilizer (Rossi et al., 2020). In this study, solid AD fraction was applied at higher rates than the other treatments, showing comparable or better performances than those of mineral fertilizer. On the one hand, this confirms the good potentialities of by-products as SD for sustaining crop production (Morra et al., 2021; Riva et al., 2016; Tsachidou et al., 2019; Walsh et al., 2012) and, on the other, from a methodological point of view, supports the adoption of different N rates when different fertilizers (e.g., organic and mineral) are used, to homogenize crop performances and evaluate the cropping system sustainability in a holistic way (Grillo et al., 2021).

Digestate reuse as a fertilizer might close the nutrient cycle and give new insight into the circular economy. Moreover, the substitution of fossil fuel-derived fertilizers is one of the main drivers of sustainable development goals (U.N, 2015). A strong interaction was revealed between soil and cropping system sustainability as evaluated with NUE according to EU Nitrogen Expert Panel (2015). Indeed, contrary to what was reported for the agronomic performances, the efficiency of digestate fraction was higher in finer (F1) than in coarser soil (F2). This might be explained by a higher risk of nutrient leaching (Singh et al., 2010) and, an higher susceptibility of sandy soil to adverse factors (e.g., water stress) (Morari et al., 2018). The application of the NUE index exhibited to be an easy tool to evaluate the agri-environmental sustainability of the cropping systems at a spatial scale. From a methodological perspective, the applied criteria –i.e., NUE limits– might be optimized for the specific crop. In particular, the minimum productivity limit might be raised to ca. 200 kg N ha^{-1} in the case of silage maize. The greater NUE performances were observed under systems using mineral fertilizer compared to organic ones and sometimes was calculated > 100%. It should be recalled that the NUE was calculated as the ratio between N uptake (i.e., product between silage maize dry biomass and N concentration in biomass) and N input with fertilizer (i.e., N application rate) according to the EU Nitrogen Expert Panel (2015). Therefore, a NUE > 100% means the crop needs were greater than applied N rate and, in turn, it might suggest the crop used also the N present in the soil. On the one hand, nutrients mining from highly fertile soils may be considered a good practice, as it results in a high resource use efficiency and it may decrease potential nutrient losses (EU Nitrogen Expert Panel, 2015). On the other, if this practice is applied on a longer-term, it might raise the risk of soil nutrient mining and, consequently, soil degradation, erosion and poverty (Sanchez, 2002). The high efficiency of mineral fertilizer is well-known and has been previously reported using the same NUE approach (Grillo et al., 2021). Mineral fertilizer NUE was further increased when applied in VRA at F1 where also greater soil NO_3-N content was evidenced (data not shown). However, the optimization of N input by maximizing AESI reduced the potential benefits of VRA by narrowing at 30–40 kg N ha^{-1} the differences among the homogeneous zones. Harmel et al. (2004) previously reported lower NO_3^-- and NO_2^--N concertation in VRA runoff water compared to mineral fertilizer uniform application. In addition, Stamatiadis et al. (2020) observed that the VRA of mineral fertilizer improved the N recovery and, in turn, the fertilizer efficiency. The high fraction of plant-available NH_4^+-N (i.e., >45% of total N) in liquid digestate fraction might also explain the high NUE observed in the LD+ and VRA-LD+ treatments at both farms. Contrarily, the solid digestate fraction often showed poor minimum NUE (i.e., < 50%) in this study. This could be attributed to the nature of organic fertilizer (i.e., organic N > 70%) and agricultural practice (e.g., fertilizer fractionation and timing) (Ehmann et al., 2018). The solid digestate previously exhibited lower apparent N recovery compared to other fertilizers (Cavalli et al., 2016; Grillo et al., 2021) due to the high

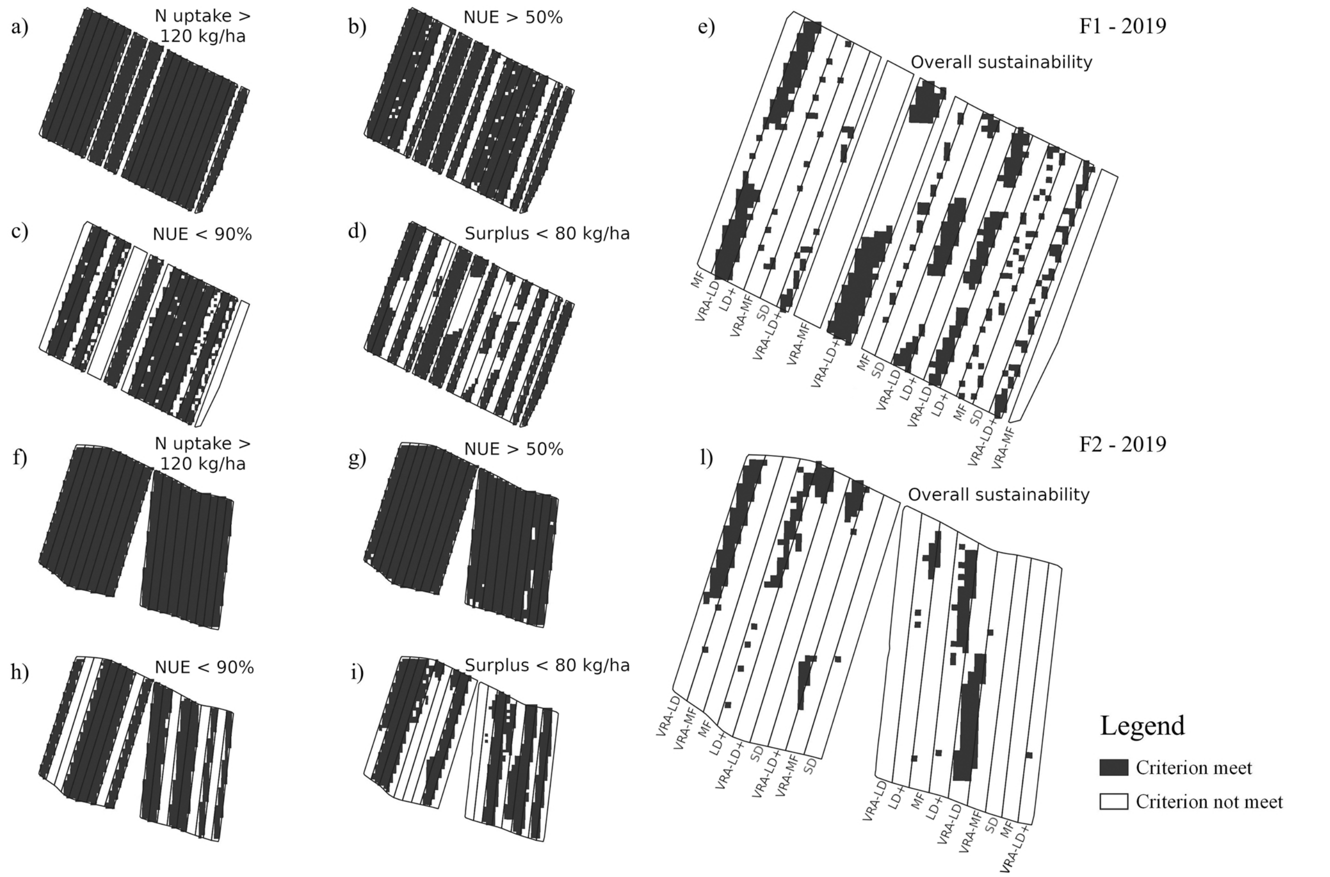

Fig. 7. Cropping system sustainability evaluation at F1 (a-e) and F2 (f-l) in 2019. Minimum productivity (a and f), NUE > 50% (b and g), NUE< 90% (c and h), surplus < 80 kg ha^{-1} (d and i) and overall sustainability (e and l). Dark pixels indicate the criterion met.

presence of N in organic form (Möller and Müller, 2012; Peters and Jensen, 2011), not readily available for the actual crop. Our results confirmed local estimates of SD NUE which averaged 50% (Regione del Veneto, 2021). In this study, the optimal N rate was identified at higher SD doses compared to other treatments due to the lower NUE. The higher SD rates were able to compensate the lower N release as shown by the similar mineral N content in the soil profile compared to the other treatments (data not shown). Despite providing a limited N source in the short term (Abubaker et al., 2015), solid digestate is expected to provide a gradual N release in the medium term (Tsachidou et al., 2019). Therefore, also the SD efficiency might be better evaluated considering a longer term. The NUE of liquid digestate added with nitrification inhibitor was increased when applied in VRA, at least in finer soil of F1. The liquid digestate efficiency was further increased when the nitrification inhibitor was added in 2019 at both farms and in 2020 at F1. Most likely, heavy rainfall close to LD distribution dominated the nitrification inhibitor effect. This might suggest that nitrification inhibitor reduces nitrate leaching caused by rainfall and increase N retention in soil, providing both environmental and economic benefits (Giacometti et al., 2020). Kyveryga and Blackmer (2014) specified how nitrification inhibitors might produce profitable yield responses when spring and summer rainfall exceed the long-term averages by more than 40%. In addition, Chiodini et al. (2019) found these products effective in reducing the N_2O emissions. For these reasons, these products may be a key factor for future agriculture in a climate change scenario.

5. Conclusion

The studied treatments demonstrated that the adoption of different N rates and distribution methods should be adopted when different fertilizers (e.g., organic and mineral) are used, to obtain sustainable cropping systems.

Liquid digestate fraction represented a reliable alternative to mineral fertilizers allowing production comparable to those of synthetic fertilizers, especially when combined with variable-rate application and nitrification inhibitor. However, specific soil characteristics might be carefully considered to identify the best available distribution methods able to optimize the digestate rate and reduce, at the same time, its environmental impact. The solid digestate fraction exhibited agronomic performances similar to those of mineral fertilizers but still present some concerns regarding its efficient use. As for other solid organic fertilizers (e.g., farmyard manure), longer-term studies should consider also the benefits related to the carbon cycle and soil structure.

In conclusion, digestate fractions applied with the best available methods might be an asset for the circular economy, allowing the fulfillment of the European Community's goals to decarbonize gas markets and reduce methane emissions.

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CRediT authorship contribution statement

Ilaria Piccoli: Methodology, Formal analysis, Investigation, Writing – original draft preparation, Writing – review & editing, Visualization. **Federico Grillo:** Methodology, Formal analysis, Investigation, Data curation, Writing – original draft preparation, Writing – review &

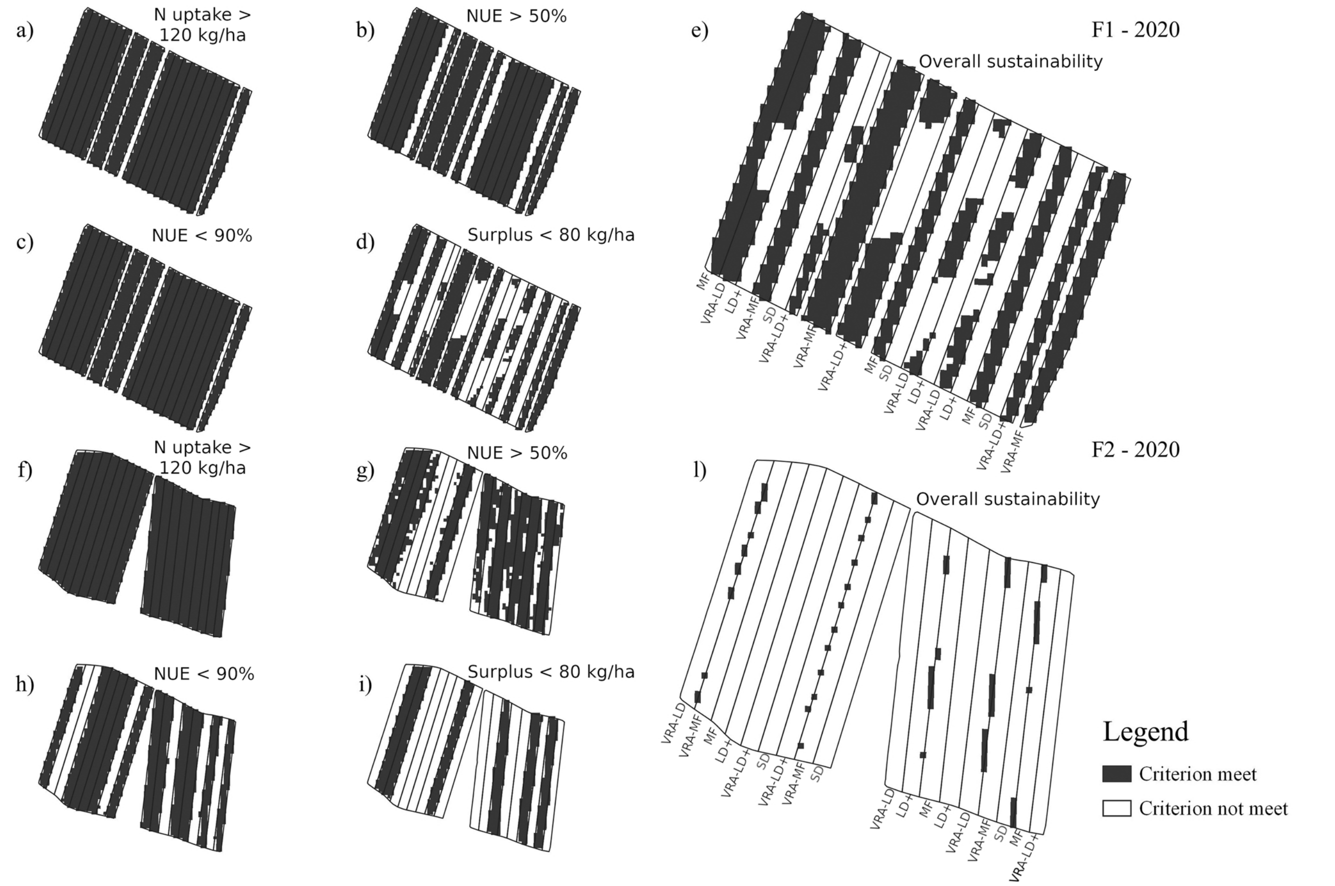

Fig. 8. Cropping system sustainability evaluation at F1 (a-e) and F2 (f-l) in 2020. Minimum productivity (a and f), NUE > 50% (b and g), NUE< 90% (c and h), surplus < 80 kg ha^{-1} (d and i) and overall sustainability (e and l). Dark pixels indicate the criterion met.

Table 5
Percentage of the treatment area meeting the sustainability criteria. Data are expressed as mean ± standard error.

		Treatment	Min. productivity	NUE > 50%	NUE < 90%	Surplus < 80 kg ha^{-1}	Sustainability
F1	**2019**	MF	100 ± 0	100 ± 0	0 ± 0	100 ± 0	0 ± 0
		VRA-MF	100 ± 0	100 ± 0	0 ± 0	100 ± 0	0 ± 0
		LD+	100 ± 0	100 ± 0	100 ± 0	0 ± 0	0 ± 0
		SD	100 ± 0	0 ± 0	100 ± 0	0 ± 0	0 ± 0
		VRA-LD	100 ± 0	100 ± 0	100 ± 0	70 ± 17	70 ± 17
		VRA-LD+	100 ± 0	100 ± 0	99 ± 1	66 ± 24	65 ± 23
	2020	MF	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0
		VRA-MF	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0
		LD+	100 ± 0	100 ± 0	100 ± 0	5 ± 4	4.7 ± 1
		SD	100 ± 0	0 ± 0	100 ± 0	0 ± 0	0 ± 0
		VRA-LD	100 ± 0	100 ± 0	100 ± 0	63 ± 15	63 ± 15
		VRA-LD+	100 ± 0	100 ± 0	100 ± 0	66 ± 23	66 ± 23
F2	**2019**	MF	100 ± 0	100 ± 0	0 ± 0	100 ± 0	0 ± 0
		VRA-MF	100 ± 0	100 ± 0	0 ± 0	100 ± 0	0 ± 0
		LD+	100 ± 0	100 ± 0	100 ± 0	30 ± 18	30 ± 18
		SD	100 ± 0	100 ± 0	100 ± 0	0 ± 0	0 ± 0
		VRA-LD	100 ± 0	100 ± 0	100 ± 0	37 ± 35	37 ± 35
		VRA-LD+	100 ± 0	100 ± 0	100 ± 2	15 ± 67	15 ± 67
	2020	MF	100 ± 0	100 ± 0	0 ± 0	100 ± 0	0 ± 0
		VRA-MF	100 ± 0	100 ± 0	0 ± 0	100 ± 0	0 ± 0
		LD+	100 ± 0	62 ± 19	100 ± 0	0 ± 0	0 ± 0
		SD	100 ± 0	0 ± 1	100 ± 0	0 ± 0	0 ± 0
		VRA-LD	100 ± 0	95 ± 5	100 ± 0	0 ± 0	0 ± 0
		VRA-LD+	100 ± 0	9 ± 15	100 ± 2	0 ± 0	0 ± 0

editing, Visualization. **Matteo Longo:** Formal analysis, Writing – review & editing, Visualization. **Ivan Furlanetto:** Conceptualization, Writing – review & editing, Project administration. **Francesca Ragazzi:** Methodology, Investigation, Writing – review & editing. **Silvia Obber:** Methodology, Investigation, Writing – review & editing. **Tiziano Bonato:** Investigation, Writing – review & editing. **Francesco Meneghetti:** Writing – review & editing. **Jacopo Ferlito:** Writing – review & editing. **Luca Saccardo:** Writing – review & editing. **Francesco Morari:** Conceptualization, Methodology, Writing – review & editing, Supervision. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2023.126811.

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