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Production efficiency, costs and environmental impacts of conventional and dynamic forage systems for dairy farms in Italy

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ABSTRACT

Over the last few decades, scientists, decision-makers, consumers and the more volatile marketplace impose to dairy farms to manage forage systems more sustainably, while maintaining profitability. Hence, shifting from a conventional forage system based mainly on monocropping corn (CONV_FS) to a more flexible one, defined as dynamic forage system (DYN_FS), that is based on increasing on-farm cropping of leguminous species, double cropping, scheduling of forage cuts to early stages of growth, and the adoption of silage conservation in place of haymaking, could help increasing overall system sustainability. A multi-year study, conducted on two commercial high productive dairy farms, analyzed this shift from an agronomic, economic and environmental point of view. The two farms milked 127 and 262 cows, farmed 56 and 102 ha, and had a milk production intensity of 20 and 26 t/ha per year, respectively. All the data necessary to determine dry matter (DM) yield, forage quality, in terms of crude protein (CP) and metabolizable energy (ME), the nitrogen balance, agrochemical management, the energy balance and efficiency, labor use, economic budgets, and carbon footprint of the two forage systems were on farm measured and collected. One hectare of tillable land, 1 t of DM or CP, and 1 GJ of ME were chosen as functional units. The adoption of DYN_FS increased overall system efficiency (increased DM, CP and ME yields per hectare), reduced reliance on external inputs (chemical N and pesticides), led to a more equilibrated N balance, reduced agrochemical use intensity and potential ecotoxicological impacts, increased energy use efficiency and reduced carbon footprint when compared to CONV_FS. Shifting from DYN_FS to CONV_FS had also a positive effect on the costs sustained per hectare of tillable land, whereas the labor requirements increased slightly on a per hectare basis, but decreased relative to the chosen functional units. Finally, DYN_FS provided more ME and CP than CONV_FS, but maintained a similar milk production and quality.

We have concluded that the new dynamic forage system DYN_FS has the potential of being profitable and could enhance production efficiency and environmental quality in the more intensive forage systems adopted on dairy farms in the Po plain in Italy.

1. Introduction

The intensification of dairy farming systems has been accompanied by the development of corn silage and intensively fertilized grasses throughout Europe, while the protein supplementation of dairy rations has been left to purchased soybean meal, which is predominantly produced overseas (Borreani et al., 2013; Lehuger et al., 2009). In the same way as other European countries, the Italian dairy sector has also been affected by an intensification process, as a result of an increase in the number of dairy cows per hectare of land, the acquisition of genetically improved dairy cattle, and an increase in concentrates in the diet (Alvarez et al., 2008; Bava et al., 2014), and this has resulted in significant effects on the efficiency, and thus on the economic results of the farms.

Italy produces about 11.5 million tonnes of milk a year, which represent about 7.5% of the milk produced in the EU-28 (CLAL, 2016). Around 80% of Italian milk comes from the intensive farming systems in the Po Plain, where the high producing Italian Holstein breed is reared (Bava et al., 2014; Borreani et al., 2013). There is currently a lack of arable land in the Po plain and land charges/rents are high. Over the years, the climate and the high soil fertility of the area have favored the cultivation of crops that are thought to produce a high dry matter

Abbreviations: EUE, energy utilization efficiency; FCM, fat corrected milk; CONV_FS, conventional forage systems; DYN_FS, dynamic forage system; ME, metabolizable energy; CP, crude protein

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(DM) yield per hectare and to be more suitable for an easy conservation by ensiling (Borreani et al., 2013). Corn for silage is the most frequently cultivated crop, to the detriment of forage legume crops and other annual grasses, which are considered to be low producing crops that are difficult to ensile (Borreani et al., 2013; Peyraud et al., 2009). As a consequence, most of the dairy farms operating in the Po plain have abandoned annual forage grasses and legumes and have specialized in corn silage production, with the aim of being self-sufficient for their animal feeding energy requirements, although they buy most of the protein sources. These changes have been favored to a great extent by an era of low-cost soybean meal on the market (Wolf, 2010) and of cheap non-renewable energy, which has encouraged high fertilizer and pesticide inputs (Peyraud et al., 2014). Hence, the dairy forage systems of the Po plain are currently extremely simplified, with corn crops being grown on up to 90% of the utilized agricultural area. Such a system relies on a high external input and non-renewable energy consumption, with an increasing demand for nitrogen fertilizers and agrochemicals to maintain the high DM yield of mono-cropped corn, and concerns have thus arisen about the environmental impact of intensive forage systems on dairy farms, the traceability of supply chains and about food security (Lehuger et al., 2009). Furthermore, the volatility of the market prices of corn and soybean that has resulted in an increased uncertainty about concentrate costs makes the corn-silage based cropping system no longer economically, other than environmentally, sustainable for dairy farms (Wolf, 2012).

Therefore, in order to maintain farm competitiveness, to decrease feeding costs and to increase farm protein self sufficiency (Peyraud et al., 2014; Wolf, 2012), producers need to develop more sustainable cropping systems by considering crop sequencing to take advantage of the inherent internal resources (synergisms, nutrient cycling and soil water) while also capitalizing on external resources, such as the weather, neighboring farm interrelationships, markets, government programs and new technologies (Liebman et al., 2008; Tanaka et al., 2007). Tanaka et al. (2002) developed the concept of *dynamic cropping systems* and defined them as a long-term strategy of annual crop sequencing that optimizes crop and soil use options, while attaining production, economic and resource conservation goals by using sound ecological management principles.

From our perspective, this means growing more crops (both annual and perennial) in the forage system and re-designing crop rotations and intercropping in such a way as to develop a more self-sufficient, integrated and closed-loop livestock and vegetal production system, using an agro-ecological and ethological approach with the final objective of achieving an eco-functional intensification of sustainable livestock production (Guyader et al., 2016; Tilman et al., 2002). Forage production systems that serve dairy farms should be modified to attain an increased protein self-sufficiency in order to partially or totally replace soybean and other protein concentrate imports and to increase the amount of crops that are not suitable as food and fiber for humans but utilizable by livestock. Because of its high starch content, corn silage is a good source of ruminally fermentable carbohydrates, but it is low in protein (Brito and Broderick, 2006). A new forage system, which has hereafter been defined as *dynamic forage system*, should be based on the setting up of a crop sequence and diversification that are able to satisfy the requirements of high producing dairy cows, by providing forages and feeds with high concentrations of protein and energy, through early cutting strategies associated with efficient forage conservation techniques, and at the same time reducing external inputs, economic costs and environmental impacts (Tabacco et al., 2016). This crop sequence is dynamic, in relation to the market prices of the driving commodities for protein (soybean meal) and energy (corn grain) supply for dairy rations. In particular, it integrates the potential production of starch by corn, with other forages (grasses and legumes) that could have high nutritive and feeding value for dairy cows if produced at an early stage of growth (Borreani et al., 2007; Valente et al., 2000; Zebeli et al., 2010) and preserved by ensiling (Colombari et al., 2001).

Compared to corn silage, conserved Italian ryegrass, alfalfa and grass-legume mixtures are complete feeds, which are rich in energy, protein and minerals (Brito and Broderick, 2006; Peeters, 2008; Valente et al., 2000) and, if harvested at a young maturity stage, may be used to support a reasonable milk production, even without supplements (Randby et al., 2012; Steinshamn and Thuen, 2008). Furthermore, alfalfa, Italian ryegrass and corn are also complementary for agronomic reasons. Italian ryegrass, planted in late summer or early autumn, grows over winter, thus contributing to the soil covering (i.e. reducing soil erosion and nitrate leaching), and it could provide supplemental high quality forage if it is harvested in early spring before establishment of the subsequent corn crop. Alfalfa can be successfully used in a crop rotation with corn, as it supplies nitrogen to agro-ecosystems via its unique ability to fix atmospheric N_2 (Russelle et al., 2001), increases soil organic matter (Peoples et al., 1995) and offers the possibility of differing harvest schedules, thus contributing to reducing labor and equipment constraints (Brito and Broderick, 2006), as well as stimulating the productivity of the subsequent crops. Diversifying cropping systems and including forages in rotation with annual crops can help to reduce yield losses from insects and diseases (Altieri, 1999), to reduce weed community density and to minimize the need for herbicides (Anderson, 2005; Liebman and Dyck, 1993), thus contributing to the improved resilience of cropping systems. Furthermore, economic and environmental benefits are enhanced when crop rotations with forages are set up in forage systems to serve livestock enterprises, especially dairy farms (Russelle et al., 2007).

Over the last few decades, several studies have been conducted to evaluate environmental impacts and agronomic efficiency improvements with the aim of showing the cumulative effects of crop management strategies on crop yields, profitability, weed competition and soil properties (Alluvione et al., 2011; Coulter et al., 2011; Davis et al., 2012; Deike et al., 2008). However, most of these studies were conducted under controlled conditions on confined experimental plots of limited dimensions, focusing on one or a few aspects of crop management. This approach could lead to divergent results and limited suggestions, and points out the need for a better understanding, directly on farm, of the performance of different cropping systems. On-farm research, under conditions that are representative of those encountered by producers, that consider to make the transition from standard production practices to new dynamic forage systems are therefore needed to help them make right input and practice changes (Greene and Kremen, 2003; Karlen et al., 2007). The development of farmer-researcher partnerships and system approaches will improve our understanding of the complex interactions that take place between farming systems and the environment (Karlen et al., 1995), and could give us a more complete vision of the processes involved in the management of a cropping system that needs to produce feedstuffs for lactating cows (Long and Ketterings, 2016).

In consideration of all aforementioned aspects, we conducted a multiyear on-farm study on two commercial dairy farms with the aim of testing the hypothesis that dynamic forage systems can provide yields (in terms of DM, CP and ME) that match or exceed those obtained from the mono-cropped corn silage systems that are conventionally adopted in NW Italy, while reducing the environmental impact of the production system and the cost of the produced feedstuffs. We focused on evaluating how such an alternative cropping system, coupled with highly efficient forage conservation practices, affect the nitrogen, energy, labor and economic budgets as well as the carbon footprint of dairy forage systems, compared with the crop management systems conventionally adopted in most of the dairy farms operating in the Po plain in Italy.

2. Materials and methods

2.1. Farm selection and experimental approach

The experiment was conducted over an 8 year period on two commercial dairy farms (on average 127 and 262 milking + dry cows and 135 and 294 heifers from birth through calving), which farm 56 and 102 tillable hectares of land, respectively. The intensity of milk production is approximately 20 and 26 t/ha per year for Farm 1 and Farm 2, respectively. The two farms are located in Piedmont (44°52′35″N and 7°45′25″E, Farm 1, and 44° 27′24″N and 7°43′28″E, Farm 2).

The soils, Gleyic Luvisol (Farm 1) and Haplic Luvisol (Farm 2), are deep and well drained on both farms, with prevailing sandy loam and loam textures in the 0–30 cm horizon on Farm 1 and Farm 2, respectively. The elevation on Farm 1 and Farm 2 ranges from 237 to 242 and from 399 to 420 m above sea level, respectively. The local climate has been classified as temperate sub-continental, with a long potential growing season and a mean annual rainfall ranging from 700 to 1000 mm. moreover, there are two main rainy periods that occur during spring (April and May) and autumn (September–November). The mean annual temperature is 12.1 °C and 12.3 °C, for Farm 1 and Farm 2, respectively.

Both farms have changed from a conventional corn silage forage system (CONV_FS) (first 3 years) to a dynamic forage system (DYN_FS) (last 3 years) with a transition period of 2 years between the two surveyed forage systems (Transition Period). Before the initiation of the experiment, the two farms had been managed for at least 5 years with a corn grain – corn silage mono-cropping production system on about 70% of the used agricultural area (UAA). In both systems, all the summer crops were fully irrigated, on average 3–4 times for corn, 2–3 times for alfalfa and rotational grassland, and once for soybean and sorghum. The main variations in the forage system and management of forage harvesting and conservation from CONV_FS to DYN_FS are summarized in Table 1.

2.1.1. Conventional forage system (CONV_FS)

This scenario is representative of the current cropping management system of about 80% of the intensive farming systems located in the Po Plain in Italy (Borreani et al., 2013; Gaudino et al., 2014; Zucali et al., 2018). The dominant crop is mono-cropped or double-cropped corn with Italian ryegrass, and, to a lesser extent, rotational grass meadows, forage sorghum and alfalfa. The corn crop is mainly harvested as silage or dry grain, when the whole crop corn silage requirements of the herd have been satisfied. In many cases, some of the corn grain is not used for animal feeding and it is therefore sold on the market. Alfalfa and grass meadows are mainly harvested at a late stage of maturity, cut three to four times a year and conserved as hay. Italian ryegrass is harvested in late spring (flowering stage, mid-May) as hay. Forage sorghum, if present, is harvested once a year as whole-crop silage.

Table 1
Variations of the cropping system management and forage conservation techniques from the two forage systems on the two studied farms. Forage systems were CONV_FS = conventional forage systems and DYN_FS = dynamic forage system.

Item	CONV_FS	DYN_FS
Corn double cropped with Italian ryegrass	baseline	increase
Corn for whole-crop silage	baseline	decrease
Corn harvested for dry grain	yes	no
Corn harvested as high moisture ear silage	baseline	increase
Alfalfa hay (late maturity)	yes	no
Alfalfa silage (early maturity)	no	yes
Italian ryegrass and/or rotational meadow hay (late maturity)	yes	no
Italian ryegrass and/or rotational meadow silage (early maturity)	no	yes

2.1.2. Transition period

This period refers to a two-year conversion period, from the conventional corn based system (CONV_FS) to a new dynamic forage system (DYN_FS). The conversion of the farms has involved: (i) an increase in UAA cultivated with alfalfa to substitute corn for silage and an increase in the double Italian ryegrass-corn crop; (ii) harvesting of all the corn as whole crop silage or whole ear silage; (iii) adoption of different management systems for forage harvesting (cutting at early stage of growth) and conservation (ensiling instead of haying), with the aim of increasing the home-grown production of crude protein and metabolizable energy, by producing forages with a higher crude protein content and low and highly degradable NDF.

2.1.3. Dynamic forage system (DYN_FS)

In this new scenario, the forage system has mainly been based on a double Italian ryegrass-corn crop and an alfalfa meadow, whereas forage sorghum was grown on areas less suitable for growing corn. The corn harvested as whole crop silage decreased, whereas the corn harvested as whole ear silage increased, compared to the baseline scenario of CONV_FS; in this new system, corn production never exceeded the feeding requirements of the dairy cows and was never harvested as dry grain. Alfalfa was grown on about 30–50% of the UAA, and was harvested as wilted silage (50% DM) at an early stage of growth, six to seven times a year. Italian ryegrass was harvested once/twice a year as wilted silage (50% DM) at an early stage of growth (boot stage, mid-April, and mid-May in the case of a second cut). Forage sorghum was managed in the same way as for CONV_FS.

2.2. Dry matter yield and forage quality

The DM and quality (CP and ME) recovery were determined using the total-in vs. total-out method proposed by Köhler et al. (2013) as the measurement principle.

The fresh matter yield was measured for each harvested grain and forage using the sum of the weights of all the loads from each field measured using platform truck-scales, that were located on the farms. Fresh matter yield was recorded each year, for each crop, from all the field farmed by the two farms. Each year, all the on-farm produced grain and forage crops were routinely sampled to determine DM content and nutritional quality. One composite sample (3–6 subsamples) was prepared at harvesting (haying or ensiling) for each forage (and each cut, i.e. six/seven cuts of alfalfa every year from 6 and 11 fields, in Farm 1 and 2, respectively, or corn harvested as silage from 7 and 13 fields, in Farm 1 and 2, respectively), and 1–10 composite samples, from each forage (different silage bunkers, different lots of baled silage or hay), were made at the total mixed ration (TMR) preparation time. Grain crops were sampled from the silo at the TMR preparation time (5–10 samples each year). Furthermore, each TMR load was weighed and all weights recorded digitally along all the year.

Each sample was split into two sub-samples. The first sub-sample was analyzed to establish the DM content by oven drying it at 80 °C for 48 h. The second sub-sample was dried for qualitative analyses in a forced-draft oven to a constant weight at 65 °C, air equilibrated, weighed and ground in a Cyclotec mill (Tecator, Herndon, VA, USA) to pass a 1 mm screen. The dried samples were analyzed for total nitrogen (TN), according to the Dumas method (method number 992.23, AOAC, 2005), using a Nitrogen Micro-N analyzer (Elementar, Hanau, Germany), for crude protein (CP) (total N × 6.25), for ash by ignition to 550 °C for 3 h (method number 942.05, AOAC, 2005), and for ether extract (EE), using the Soxhlet method according to AOAC (method number 920.39; AOAC, 2005). Neutral detergent fiber (aNDF) was analyzed using a Raw Fiber Extractor (FIWE, VELP Scientifica, Usmate Velate, Italy), with the addition of heat-stable amylase (A3306, Sigma Chemical Co., St. Louis, MO), and was expressed on a DM basis, including residual ash, as described by Van Soest et al. (1991). Acid detergent fiber (ADF) and acid detergent lignin were analyzed (Robertson and Van Soest, 1981) and expressed on a DM basis, including residual ash.

The calorific values (gross energy, GE) were derived from the chemical analysis (ash, protein, fat and N-free extract contents) as described by Hülsbergen et al. (2001). Organic matter digestibility (OMD) was determined according to the two-stage rumen fluid technique (Tilley and Terry, 1963). Metabolizable energy and net energy of lactation were calculated according to Andrieu and Demarquilly (1987).

The DM yield, CP yield and the amount of metabolizable energy (ME) available for animal feeding were calculated on the basis of the fresh matter yields that were available at the time of TMR preparation, taking into account all the losses that could happen over the whole feed production process. The DM yield, CP yield and the amount of ME were then referred to 1 ha of farm surface.

2.3. Nitrogen balance

The nitrogen balance approach used in this study involved calculating the difference between the total imported nitrogen and that exported at the cropping system-scale, and the results were presented on a per-ha basis (Gourley et al., 2012; Oenema et al., 2003). Nutrient-use efficiency was calculated as the total exported nitrogen divided by the total imported nitrogen, and it was expressed as a percentage (Gourley et al., 2012). The data requirements included the DM yields and N concentrations of all the forms of utilized inorganic and organic fertilizers, soil ameliorants, seeds and harvested grain and forages. Estimates of the N fixation inputs were also included, whereas atmospheric deposition and nitrogen in the irrigation water were not considered.

The mass of purchased inorganic fertilizers was recorded as were the used standard nitrogen concentrations, as provided by the commercial suppliers. The utilized manure and slurry were sampled at the time of field spreading (2–4 samples at each spreading time) and the analyzed nitrogen concentration was applied to the nitrogen balance calculations.

2.4. Agrochemical management

The indicator set proposed in the SOSTARE model (Paracchini et al., 2015) was used to assess the agrochemical use intensity at the cropping system level. In short, we considered: the proportion of UAA that was not treated with agrochemicals in a year; the frequency of application, which was calculated as the average number of pesticide applications per hectare of UAA in relation to the recommended standard dose of each active ingredient; the potential eco-toxicological impact of agrochemicals estimated using the Load Index, calculated for three groups of non-target organisms (rats, algae and honeybees).

2.5. Energy balance and efficiency

As in Alluvione et al. (2011), a “process analysis” methodology was adopted, in which the support energy (energy inputs for crop cultivation) and outputs were traced by following physical material flows. Human labor, solar energy and changes in the soil carbon stock were not considered. After quantification, the physical material flows were transformed into energy flows using specific energy equivalents (Alluvione et al., 2011; Hülsbergen et al., 2001; Paracchini et al., 2015). The energy inputs in the cropping system include a direct energy input and an indirect energy input. Direct energy refers to diesel fuel, lubricants and electricity. Indirect energy includes the energy input for resources, manufacturing machines and storage facilities.

The energy input categories were: seeds, synthetic fertilizers, agrochemicals, plastic, field operations and product handling were considered. Grain and forage handling included both hauling harvested material out of the field and drying or ensiling the material to standard storage conditions.

Manure was assumed to be free (i.e. a waste product of a livestock operation), and its only energy cost was the labor and the energy consumed by machinery for application (Cruse et al., 2010; Liebman et al., 2008). Energy output was calculated on the basis of DM yields available for animal feeding after conservation and their gross energy content (calorific values), whereas the non-harvested biomass (e.g. crop residues) was not considered.

2.6. Labor requirement

All the labor input data were recorded by farm operators during the experiment. The time (h) required to complete a field operation (performed by farm workers, both family or non-family employees and/or contractors) was recorded and expressed as h/ha. Labor requirements were calculated on a yearly basis as the sum of all the hours required to grow, harvest and arrange the conservation of all the crops. The hours of labor for manure and slurry application were included.

2.7. Economic performance

The economic performance of the different cropping systems was assessed according to Liebman et al. (2008) using (i) data concerning machinery operations (time, labor and fuel consumption), inputs, and yields; (ii) the cost of seeds, fertilizers, agrochemicals, plastic and silage inocula according to the local agricultural dealers; (iii) agricultural engineering and farm business management databases for the cost, depreciation and repairs of structures and machinery; (iv) contractor charges when an operation was made by a contractor. Labor costs for farm personnel (family workers) was set to 16 €/h. All the prices and costs refer to the year 2017. The economic efficiency was calculated as the total amount of money (Euros) spent to cultivate 1 ha of UAA or to produce a unit of DM (t), CP (t) or ME (GJ).

2.8. Carbon footprint

The Carbon Calculator (Tuomisto et al., 2015) was used to compute the emissions from the whole forage system over a year. The direct GHG emission sources considered were: CO_2 emissions from fuel use by farmers and contractors for field operations, CH_4 emissions from manure management and application in the field, N_2O emissions from manure and from soils, due to the use of organic and synthetic N fertilizers. In addition, the upstream emissions generated outside the farms, including emissions from the production and transportation of farm inputs, and N_2O emissions from NH_3 volatilization and from N leaching and runoff, were incorporated.

In the Carbon Calculator, the emissions related to soil C stock changes were not included in the total C footprint of the farm, but the results were reported separately, and the changes in soil C stocks were estimated on the basis of the IPCC (2006) guidelines.

2.9. Dairy herd requirements and fulfillment

All the produced feedstuffs were fed to farm animals (milking cows and replacement herd), and all the purchased feeds (soybean meal, grain distillers with solubles, and mineral/vitamin supplements), necessary to satisfy the animal requirements, in terms of growth and production, were measured for each forage system on a one year basis. On both farms, the nutrient requirements of milking cows for ME, CP and DM intake were calculated relative to their average milk production and milk quality collected over the entire studied period, using version 6.1 of the CNCPS model (Van Amburgh et al., 2015). On both farms, the nutrient requirements of heifers and dry cows for ME, CP and DM intake were calculated relative to the average bodyweight and nutrient requirements of pregnant cows, using the CNCPS model, version 6.1.

2.10. Functional units

The forage systems studied in this research had the aim of producing feedstuff to be fed to lactating dairy cows and replacement herds, and the environmental goal of this type of analysis is to minimize the environmental impacts per product unit (Nemecek et al., 2008). As a consequence, we chose 1 hectare (ha) of tillable land, 1 t of DM, 1 t of CP and 1 GJ of ME as the functional units.

2.11. Data analysis

The DM, energy and protein yields, nitrogen and energy balances, labor and costs, and carbon footprint were analysed for their statistical significance via analysis of variance, with their significance reported at a 0.05 probability level using the general linear model of the Statistical Package for Social Science (v 17.0, SPSS Inc., Chicago, Illinois, USA). The data were analysed utilizing the forages systems (CONV_FS and DYN_FS) and farms (1 and 2) as fixed factors, with three replicates, with data from the two forage systems pertaining to individual years as replicates in the statistical model.

3. Results

3.1. Dry matter yield and forage quality

The crops grown on the two farms and in the two forage systems, as well as their proportion of UAA, are reported in Table 2. The proportion of UAA with Italian ryegrass double-cropped with corn and alfalfa increased from CONV_FS to DYN_FS on both farms, whereas the proportion of UAA with corn decreased. A higher proportion of corn was harvested as whole crop ear silage for DYN_FS than for CONV_FS on both farms.

The DM yield, CP yield and ME yield of the crops, measured at the end of conservation before feeding to the animals, are reported in Tables 3–5, respectively. On average, the DM, CP and ME yield per hectare increased from CONV_FS to DYN_FS, with Farm 1 showing the highest values in DYN_FS. Alfalfa was the crop that showed the highest increase in DM yield on both farms for DYN_FS (+77% and 55% on Farm 1 and Farm 2, respectively), whereas Italian ryegrass produced less on both farms for DYN_FS. Similar trends to the DM yield were also observed for CP and ME yield on both farms.

3.2. Nitrogen balance

The nitrogen balance (kg/ha), computed at the field gate, the efficiencies of the utilized mineral and total N, and the mineral nitrogen (kg) required to produce a unit of product on the two farms for the two forage systems are reported in Table 6. Nitrogen removal by the crops and nitrogen derived from biological fixation increased, whereas the use of mineral N decreased on both farms for DYN_FS, compared to CONV_FS. As a consequence, the nitrogen surplus decreased and the total and mineral NUE increased on both farms for DYN_FS. The amount of mineral N utilized to produce 1 t of DM, 1 t of CP and 1 GJ of ME decreased for DYN_FS, compared to CONV_FS, with the decreases being higher on Farm 1.

Table 2
Total used agricultural area, UAA (ha) and crops grown in the two forage systems (proportion of UAA) for the two forage systems on the 2 farms. Forage systems were CONV_FS = conventional forage systems and DYN_FS = dynamic forage system.

	FARM 1		FARM 2	
	CONV_FS	DYN_FS	CONV_FS	DYN_FS
Whole forage system (ha)	**55.3**	**56.5**	**102.8**	**103.7**
Italian ryegrass preceding corn/sorghum in the same year	*0.35*	*0.47*	*0.07*	*0.40*
Corn	0.76	0.53	0.64	0.43
harvested as whole ear silage	*0.11*	*0.47*	*0.08*	*0.16*
harvested as whole crop silage	*0.47*	*0.06*	*0.51*	*0.37*
harvested as grain	*0.18*	*0.00*	*0.05*	*0.00*
Sorghum	0.05	0.05	0.06	0.17
Alfalfa	0.19	0.42	0.14	0.23
Rotational grassland hay	–	–	0.16	0.05
Soybean silage	–	–	0.00	0.03

3.3. Agrochemical management

The intensity of the use of agrochemicals and potential toxicological indexes are reported in Table 7. The proportion of UAA not treated with agrochemicals increased, whereas the frequency of herbicide and insecticide applications and the load indexes decreased on both farms for DYN_FS. The amount of herbicide and insecticides applied to 1 ha of UAA or utilized to obtain one unit of DM, CP or ME also decreased on both farms for DYN_FS.

3.4. Energy balance and efficiency

The direct and indirect energy flows and energy efficiency indexes are reported in Table 8. The amount of energy from fuel and lubricants, agrochemicals, chemical fertilizers and machinery decreased, whereas the energy embedded in farm structures increased for DYN_FS, compared to CONV_FS. Total energy removal and EUE increased, whereas total energy consumed and the amount of energy consumed to produce one unit of DM, CP and ME decreased, on both farms from CONV_FS to DYN_FS. The reductions were greater for energy from fertilizers, energy consumed per hectare and for energy consumed to produce 1 GJ of ME and 1 t of CP on Farm 1.

3.5. Labor requirement

The labor requirements per hectare and labor input necessary to produce one unit of DM, CP or ME are reported in Table 9. On average, the total labor requirement per tillable hectare increased slightly on both farms for DYN_FS, compared to CONV_FS, but the labor input necessary to produce one unit of DM did not differ between forage systems, whereas the labor input necessary to produce one unit of CP and of ME decreased on both farms for DYN_FS.

3.6. Economic performance

The costs for the crop production inputs and total costs per hectare of tillable land decreased on both farms for DYN_FS (Table 10). The costs sustained to obtain a unit of DM, CP and ME were lower for DYN_FS than for CONV_FS on both farms, and the magnitude of reduction was higher on Farm 1 than on Farm 2.

3.7. Carbon footprint

The carbon footprints per hectare and per unit of DM, CP and ME are reported in Table 11. The amount of CO_2-eq emitted per hectare was lower for DYN_FS than for CONV_FS, with a greater reduction observed on Farm 1 than on Farm 2. The CO_2-eq emitted to produce one unit of DM, CP and ME decreased from CONV_FS to DYN_FS, with values that were almost halved for the production of 1 ton of CP on Farm 1.

3.8. Dairy herd requirements and fulfillment

The herd performances, CP, and ME requirements are reported in Table 12. The milk production and quality did not show any differences between the two forage systems on either farm, except for a lower

Table 3
Average DM yield (t/ha) of the forage crops for the 2 forage systems and for the 2 farms. Forage systems were CONV_FS = conventional forage systems and DYN_FS = dynamic forage system.

	FARM 1		FARM 2					
	CONV_FS	DYN_FS	CONV_FS	DYN_FS	SE	S	F	SxF
Whole forage system	**15.8**	**17.1**	**14.7**	**15.9**	0.218	*	*	NS
Italian ryegrass preceding corn in the same year	*8.1*	*5.8*	*7.4*	*5.3*	0.231	**	NS	NS
Corn – whole ear silage	12.4	13.7	15.7	14.0	1.32	NS	**	*
Corn – whole crop silage	16.2	18.3	17.5	17.3	0.604	NS	NS	NS
Corn – grain	10.2	–	12.9	–	–	–	–	–
Sorghum – whole crop silage	6.2	5.6	8.9	9.9	1.21	NS	NS	NS
Alfalfa	9.0	15.9	9.3	14.2	0.113	***	*	**
Rotational grassland hay	–	–	10.4	7.8	–	–	–	–
Soybean silage	–	–	–	5.4	–	–	–	–

NS, not significant; *, **, and *** significant at P < 0.05, P < 0.01, and P < 0.001.

protein, casein and urea content for DYN_FS. The dynamic forage system provided more CP and ME to satisfy the herd nutrient requirements, and less CP and ME were purchased off-farm for DYN_FS than for CONV_FS. The CP and ME estimated from the yield and feed analyses produced by the two studied forage systems were similar to those calculated as the difference between the CP and ME herd requirements and CP and ME from the purchased feeds.

4. Discussion

The objective of this work was to verify the agronomic, environmental and economic performances of a new *dynamic forage system,* whose crop sequence and diversification is based on the capability of satisfying the requirements of high producing dairy cows in terms of high quality forages and feeds and whose crop selection is based on the market price evolution of the driving commodities for protein and energy supply for dairy ration. The results of this experiment show that the production of DM, CP and ME available for dairy cows in a more diverse cropping system (with a high proportion of alfalfa on the UAA) can be sustained at levels that match or exceed the levels that can be obtained from the conventional systems that are generally adopted in Italy, which are principally based on mono-cropping corn for silage or grain, despite reductions in agrochemical and non renewable energy use. Systems based on mono-cropped corn for silage were designed to maximize the energy yield at a farm level, but they are no longer economically or environmentally sustainable in Italy, or in other developed countries in the EU and US, and mitigation strategies should be applied to counteract their negative environmental impacts (Tilman et al., 2002). A growing number of scientists and innovative producers have been exploring new ways of improving the overall sustainability of forage systems for dairy cows by adopting several management strategies and technologies which allow successful integrated crop-livestock systems to be developed (Bell et al., 2014; Poffenbarger et al., 2017; Sulc and Franzluebbers, 2014). These management strategies and technologies include diversifying crop rotations (Russelle et al., 2007), increasing double-cropped areas in the same year by growing winter cover crops before corn (Sulc and Franzluebbers, 2014), and relying more on perennial or rotational legume forages, which not only provide livestock feed but can also be used to achieve multiple environmental benefits (Peyraud et al., 2009; Phelan et al., 2015). In this experiment, which involved changing from a conventional to a dynamic forage system that includes a higher proportion of alfalfa over the UAA, a higher proportion of double-cropped area with Italian ryegrass-corn instead of mono-cropped corn as the only crop all year round, a shift from dry corn grain to whole ear corn silage, a systematic forage cutting scheduled at early stages of growth and the adoption of silage conservation technique instead of haymaking for all grass and legume forages, has led to an increase in the sustainability of the forage system for dairy farms. Improvements in system sustainability were in particular observed, in terms of an overall increase in system efficiency, with an increase per hectare of the yield of DM, CP and ME available for animal nutrition, while purchased inputs, such as chemical N fertilizer and pesticides, were minimized. The new dynamic forage system has in particular led to a more equilibrated N balance, a reduced agrochemical use intensity and reduced potential ecotoxicological impacts, a better energy use efficiency and a reduced carbon footprint. A positive effect has also been observed for the costs sustained per hectare of tillable land, whereas the labor requirements slightly increased on a per hectare basis, but decreased relative to the production of a unit of DM, CP or ME.

In this experiment, the adoption of cutting at an earlier stage of growth for grass and forage legumes, coupled with conservation through ensiling, has allowed forages with higher concentrations of CP and ME (alfalfa, Italian ryegrass, and rotational grassland) to be

Table 4
Protein yield (kg/ha) on the 2 farms and for the 2 forage systems produced on average on each farm and for each crop. Forage systems were CONV_FS = conventional forage systems and DYN_FS = dynamic forage system.

	FARM 1		FARM 2					
	CONV_FS	DYN_FS	CONV_FS	DYN_FS	SE	S	F	PxF
Average of whole forage system	**1302**	**2304**	**1180**	**1557**	32.8	***	***	**
Italian ryegrass preceding corn in the same year	*539*	*460*	*593*	*465*	21.0	*	NS	NS
Corn – whole ear silage	957	1298	1229	1123	21.1	*	NS	**
Corn – whole crop silage	1164	1112	1156	1120	47.9	NS	NS	NS
Corn – grain	873	–	1100	–	–	–	–	–
Sorghum – whole crop silage	590	328	613	452	48.8	NS	NS	NS
Alfalfa	1424	3280	1381	2853	27.6	***	**	**
Rotational grassland hay	–	–	1073	843	–	–	–	–
Soybean silage	–	–	–	1044	–	–	–	–

NS, not significant; *, **, and *** significant at P < 0.05, P < 0.01, and P < 0.001.

Table 5
Metabolizable energy (GJ/ha) produced on average on each farm and for each crop on the 2 farms and for the 2 forage systems. Forage systems were CONV_FS = conventional forage systems and DYN_FS = dynamic forage system.

	FARM 1		FARM 2					
	CONV_FS	DYN_FS	CONV_FS	DYN_FS	SE	S	F	SxF
Whole forage system	**159**	**191**	**148**	**163**	2.23	**	**	NS
Italian ryegrass preceding corn in the same year	*68*	*62*	*64*	*59*	2.15	NS	NS	NS
Corn – whole ear silage	149	169	192	170	3.07	NS	**	*
Corn – whole crop silage	162	192	183	178	5.60	NS	NS	NS
Corn – grain	133	–	167	–	–	–	–	–
Sorghum – whole crop silage	86	55	68	75	5.45	NS	NS	NS
Alfalfa	77	163	77	144	1.87	***	*	*
Rotational grassland hay	–	–	81	62	–	–	–	–
Soybean silage	–	–	–	31	–	–	–	–

NS, not significant; *, **, and *** significant at P < 0.05, P < 0.01, and P < 0.001.

Table 6
Nitrogen balance (kg/ha) computed at the field gate, the mineral and total N utilized efficiencies, and mineral nitrogen (kg) required to produce a unit of product on the two farms for the 2 forage systems. Forage systems were CONV_FS = conventional forage systems and DYN_FS = dynamic forage system.

	FARM 1		FARM 2					
	CONV_FS	DYN_FS	CONV_FS	DYN_FS	SE	S	F	SxF
N removal by crop	208	374	188	257	5.71	***	***	**
N from mineral fertilizer	97	27	47	26	4.47	**	*	*
N from biological fixation[a]	62	139	45	75	2.23	***	***	**
N from slurry & manure	258	244	249	227	4.31	NS	NS	NS
Total N entering the system	417	411	341	328	3.05	NS	***	NS
Surplus	209	36	154	71	6.53	***	NS	**
Total NUE (N input/output ratio)	0.50	0.91	0.55	0.78	0.015	***	NS	*
Mineral NUE (N input/output ratio)	2.32	14.33	4.05	11.18	0.943	**	NS	NS
Mineral N consumed to produce:								
1 t of DM	6.20	1.59	3.21	1.66	0.314	**	*	*
1 GJ of ME	0.61	0.14	0.32	0.16	0.028	**	*	*
1 t of protein	75.9	12.0	40.0	17.0	4.09	**	NS	*

NS, not significant; *, **, and *** significant at P < 0.05, P < 0.01, and P < 0.001.
DM = dry matter, ME = metabolizable energy, NUE = nitrogen-use-efficiency.
[a] Estimated following Borreani et al. (2003).

Table 7
Agrochemical use intensity on the 2 farms and for the 2 forage systems. Forage systems were CONV_FS = conventional forage systems and DYN_FS = dynamic forage system.

	FARM 1		FARM 2					
	CONV_FS	DYN_FS	CONV_FS	DYN_FS	SE	S	F	SxF
Proportion of UAA not treated with agrochemicals	0.24	0.47	0.31	0.45	0.016	***	NS	NS
Agrochemicals – frequency of application (n/ha UAA)	3.8	1.6	3.5	2.0	0.215	**	NS	NS
Herbicides – frequency of application (n/ha UAA)	2.6	1.5	2.5	1.3	0.154	**	NS	NS
Insecticides – frequency of application (n/ha UAA)	1.1	0.2	1.0	0.7	0.103	*	NS	NS
Load Index rats (TOX unit/ha)	0.0017	0.0005	0.0026	0.0002	0.0001	***	NS	NS
Load Index fish (TOX unit/ha)	114	163	571	30	32.8	**	*	**
Load Index algae (TOX unit/ha)	610	12	117	10	60.1	*	NS	NS
Load Index honeybees (TOX unit/ha)	19.3	0.04	1.53	0.17	1.80	*	*	*
Grams of herbicide utilized to produce:								
1 t of DM	85.9	10.3	85.6	10.4	3.47	***	NS	NS
1 GJ of ME	8.5	0.9	8.5	1.0	0.364	***	NS	NS
1 t of protein	1038	80.0	1067	106	36.5	***	NS	NS
Grams of insecticide utilized to produce:								
1 t of DM	5.7	0.6	5.4	1.0	0.528	*	NS	NS
1 GJ of ME	0.6	0.1	0.5	0.1	0.051	*	NS	NS
1 t of protein	68.3	4.1	33.5	10.0	6.15	**	NS	NS
Herbicides (g a.i./ha)	1363	177	1264	165	4.72	***	**	NS
Insecticides (g a.i./ha)	89	10	39	15	0.56	*	NS	NS

NS, not significant; *, **, and *** significant at P < 0.05, P < 0.01, and P < 0.001.
DM = dry matter, ME = metabolizable energy, UAA = used agricultural area.

Table 8
Energy fluxes (GJ/ha) and efficiencies (GJ consumed per unit of product) on the 2 farms and for the 2 forage systems. Forage systems were CONV_FS = conventional forage systems and DYN_FS = dynamic forage system.

	FARM 1		FARM 2					
	CONV_FS	DYN_FS	CONV_FS	DYN_FS	SE	S	F	SxF
Direct energy								
Fuel and lubricants	13.1	11. 7	13.1	11.9	0.138	**	NS	NS
Electricity	3.97	3.74	0.02	0.00	0.136	NS	***	NS
Indirect energy								
Seeds	1.33	1.14	1.11	1.15	0.022	NS	*	*
Agrochemicals	0.41	0.05	0.38	0.05	0.019	***	NS	NS
Fertilizers	5.03	1.72	2.04	1.18	0.203	**	**	*
Plastics	1.43	1.36	0.51	0.66	0.184	NS	NS	NS
Machinery	3.33	2.98	3.34	3.05	0.035	**	NS	NS
Structures	0.24	0.30	0.21	0.27	0.004	***	*	NS
Total energy consumed	28.8	23.0	20.7	18.3	0.300	***	***	*
Total energy (GE) removal	277	303	259	280	3.81	*	*	NS
EUE	9.7	13.2	12.5	15.3	0.245	***	**	NS
Energy (GJ) consumed to produce:								
1 t of DM	1.83	1.34	1.41	1.16	0.031	***	**	NS
1 GJ of ME	0.18	0.12	0.14	0.11	0.002	***	**	*
1 t of protein	22.3	10.0	17.6	11.8	0.486	***	NS	*

NS, not significant; *, **, and *** significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$.
DM = dry matter, EUE = energy utilization efficiency: dimensionless, GE = gross energy, ME = metabolizable energy.

obtained for DYN_FS than for CONV_FS. High quality forage is recognized as an important requirement for maintaining the maximum production of dairy cows, since it allows the animal to consume more forage along with a high-energy intake to maximize production (Rotz, 2005), and the farmer to rely less on off-farm feeds and soybean meal purchased from overseas.

Furthermore, on a per year basis, the amount of DM harvested and conserved from alfalfa fields increased for DYN_FS, by about 77% and 53%, on Farm 1 and Farm 2, respectively, and positively counterbalanced the reduction, in the same forage system, of DM yield from Italian ryegrass and rotational grassland, which were cut at an earlier stage of growth than for CONV_FS. The increased alfalfa yield available for animal feeding, and the increased CP and ME concentrations of alfalfa, ryegrass and rotational grass forage, with earlier cutting and conservation through ensiling, are in agreement with data reported by Valente et al. (2000), Orloff and Mueller (2008), Kuoppala et al. (2009) and Van Dijk et al. (2015). Variations in the DM yield and in the CP and ME concentrations of the whole crop and ear corn silage were observed to a lesser extent in both systems and on both farms.

In DYN_FS, growing a winter cover crop (Italian ryegrass) on a greater proportion of UAA and harvesting in April before corn planting, did not affect the subsequent whole crop or whole ear corn silage yields, which were similar to those obtained for CONV_FS with corn grown as the only crop over the year. This result has provided the opportunity of further increasing the DM yield per hectare for DYN_FS. Many of the species promoted and utilized as cover crops can serve as excellent sources of forage for livestock, and should therefore be considered more for overall system profitability (Sulc and Franzluebbers, 2014); among those species, Italian ryegrass is one of the most promising (Borrelli et al., 2014). Furthermore, the double-cropping system that produces corn and Italian ryegrass for silage can contribute to increasing the efficiency of the use of cattle slurry and manure to avoid N leaching and other losses in intensive dairy systems and to minimizing the pollution of air and water (Trindade et al., 2009).

Another advantage of increasing the proportion of alfalfa in the cropping system concerns the possibility of relying more on biological nutrient provisioning and pest control, thus requiring fewer synthetic nitrogen fertilizer and pesticide inputs, especially on corn, to achieve

Table 9
Labor requirements (hours) per hectare or per unit of product on the 2 farms and for the 2 forage systems. Forage systems were CONV_FS = conventional forage systems and DYN_FS = dynamic forage system.

	FARM 1		FARM 2					
	CONV_FS	DYN_FS	CONV_FS	DYN_FS	SE	S	F	SxF
Slurry and manure spreading	3.4	3.6	3.5	3.5	0.066	NS	NS	NS
Soil preparation	3.6	4.1	1.9	1.8	0.035	*	***	**
Fertilizer spreading	0.6	0.2	0.3	0.3	0.012	***	*	***
Sowing	1.5	1.4	0.8	1.1	0.026	NS	***	*
Agrochemical application	1.6	0.4	0.6	0.5	0.017	***	***	***
Irrigation	3.6	3.2	4.3	3.8	0.088	*	**	NS
Harvesting, hauling and handling	8.0	7.0	3.4	3.2	0.096	*	***	NS
Silo filling and covering, grain drying	1.2	5.2	1.3	3.0	0.052	***	***	***
Total	23.5	25.2	16.2	17.2	0.159	**	***	NS
Time (h) required to produce:								
1 t of DM	1.49	1.47	1.10	1.08	0.018	NS	***	NS
1 GJ of ME	0.15	0.13	0.11	0.11	0.002	*	***	NS
1 t of protein	18.2	10.9	13.8	11.0	0.314	***	**	**

NS, not significant; *, **, and *** significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$.
DM = dry matter, ME = metabolizable energy.

Table 10
Costs (€) per hectare or per unit of product on the 2 farms and for the 2 forage systems. Forage systems were CONV_FS = conventional forage systems and DYN_FS = dynamic forage system.

	FARM 1		FARM 2					
	CONV_FS	DYN_FS	CONV_FS	DYN_FS	SE	S	F	SxF
EU subsidies	716	766	959	942	2.41	*	***	***
Land charge/rent	651	650	694	698	1.01	NS	***	NS
Crop production inputs	477	325	375	293	14.9	**	NS	NS
Fuel, electricity and lubricants	233	239	145	126	5.04	**	NS	NS
Plastic	49	45	19	46	6.91	NS	NS	NS
Repair, maintenance and insurance (machines and structures)	175	208	178	160	4.16	NS	*	*
On farm labor	356	398	244	258	8.02	**	***	NS
Contractors	288	228	270	281	21.6	NS	NS	NS
Total production cost (subtracted EU subsidies)	1513	1327	967	920	30.5	*	***	NS
Cost (€) sustained to obtain:								
1 t of DM	96	77	66	58	2.05	***	***	*
1 GJ of ME	10	7	7	6	0.24	***	***	**
1 t of CP	1166	577	822	591	32.7	***	***	**

NS, not significant; *, **, and *** significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$.
DM = dry matter, ME = metabolizable energy.

equivalent or greater yields than mono-cropped crops (Davis et al., 2012; Hunt et al., 2017). This is supported by several researches that have shown that continuous corn, depending on the soil texture, can yield 95–100% of the corn that is grown in rotations (Ashworth et al., 2016; Pedersen and Lauer, 2002). Similarly, Crookston et al. (1991), reported that annually rotated corn yielded 10% better, and first-year corn yielded 15% better than corn under monoculture.

Interest in the use of legumes as N sources declined in the years in which inexpensive forms of inorganic N fertilizer became available. However, recent increases in energy costs, increasing interest in more sustainable farming practices, concerns about environment pollution and costs linked to the protein component of dairy rations, have made forage legumes more attractive as less expensive sources of N in feed production for dairy cows (Borreani et al., 2013; Peyraud et al., 2009). In the current experiment, the average DM yield per hectare increased slightly, whereas the amount of mineral N fertilizer applied per hectare decreased by 72% and 45% from CONV_FS to DYN_FS, on Farm 1 and 2, respectively. The amount of N entering the system, through biological fixation, increased from CONV_FS to DYN_FS, but the greater proportion of UAA cropped with alfalfa in DYN_FS allowed the average removal of N per hectare to be increased by 80 and 37% on Farm 1 and Farm 2, respectively. This positively influenced the resulting surplus of N in the system, which was reduced from 209 to 36 and from to 154 to 71 kg of N/ha on Farm 1 and Farm 2, respectively, even though the average amount of N entering the system was similar for the two forage systems on the two farms.

The positive effect on N surplus, due to the greater amount of N removed by alfalfa from the system on both farms, would probably be of greater magnitude if a lower estimation of N biological fixation had been considered. In this experiment, we estimated the potential biological fixation of alfalfa utilizing results from Borreani et al. (2003), who reported a percentage of plant N, derived from symbiotic N_2 fixation, of 65% and an average amount of N fixed per year of about 325 kg N/ha in an experiment conducted on a soil with similar characteristics to the soils observed in this research, but which had not received animal manure or slurry. It is reported that symbiotic N_2 fixation decreases with the application of manure to alfalfa (Peterson and Russelle, 1991; Daliparthy et al., 1994) or when the available N in the soil increases (Phillips and DeJong, 1984). Considering the fact that many conventional dairy farms, such as those considered in the present experiment,

Table 11
Carbon footprint (kg of CO_2-eq) per hectare or per unit of product on the 2 farms and for the 2 forage systems. Forage systems were CONV_FS = conventional forage systems and DYN_FS = dynamic forage system.

	FARM 1		FARM 2					
	CONV_FS	DYN_FS	CONV_FS	DYN_FS	SE	S	F	SxF
Direct emissions from field activities								
Fuel and lubricants	740	661	715	676	9.63	*	NS	NS
Electricity	313	295	2	0	10.7	NS	***	NS
Direct N_2O emissions from soils	2120	1916	2112	2151	23.9	*	*	*
Indirect N_2O emissions from soils	39	0	41	0	2.01	**	*	*
Processing, manufacturing and transportation								
Mineral and organic fertilizers	752	327	249	178	28.9	**	***	*
Other crop inputs (seeds, pesticides)	16	14	7	4	0.66	NS	***	NS
Secondary inputs (plastics and other petrochemicals)	44	44	15	19	5.19	NS	*	NS
Fuels	89	79	86	81	1.16	*	NS	NS
Farm buildings, machinery and materials	189	207	139	163	1.09	***	***	NS
Total GHG emission (kg CO_2-eq/ha)	**4301**	**3543**	**3366**	**3273**	48.4	**	***	**
kg CO_2-eq emitted to produce:								
1 t of DM	273	207	229	206	4.61	**	*	*
1 GJ of ME	27	19	23	20	0.43	***	NS	*
1 t of protein	3330	1545	2861	2103	80.1	***	NS	*

NS, not significant; *, **, and *** significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$.
DM = dry matter, ME = metabolizable energy.

Table 12
Dairy cow and replacement herd characteristics, nutritional requirements and estimated CP and ME obtained from the forage system on the 2 farms and for the 2 forage systems. Forage systems were CONV_FS = conventional forage systems and DYN_FS = dynamic forage system.

	FARM 1		FARM 2					
	CONV_FS	DYN_FS	CONV_FS	DYN_FS	SE	S	F	SxF
Lactating cows (n)	113	113	233	235	1.23	NS	***	NS
Dry cows (n)	14	13	29	28	0.61	NS	***	NS
Replacement herd (n)	128	143	292	296	3.98	NS	***	NS
Milk total (t/year)	1121	1126	2557	2729	26.4	NS	***	NS
FPC milk total (t/year)	1086	1099	2412	2577	20.4	NS	***	NS
Milk lactation cow (t/year)	9.88	9.95	10.99	11.56	0.096	NS	***	NS
Milk fat (%)	3.72	3.82	3.52	3.58	0.037	NS	*	NS
Milk protein (%)	3.35	3.28	3.32	3.20	0.009	**	*	NS
Milk lactose (%)	4.89	4.84	4.81	4.86	0.005	NS	*	NS
Milk urea (mg/100 ml)	29	21	25	20	0.68	**	NS	NS
$\log_{10}$ somatic cell count	5.40	5.34	5.42	5.28	0.013	**	NS	NS
Casein (%)	2.58	2.56	2.57	2.51	0.005	**	*	*
Total EM (GJ) requirements of the herd	12,963	13,265	27,452	28,371	221	NS	***	NS
Total CP (t) requirements of the herd	185	191	397	408	2.64	NS	***	NS
EM (GJ) in purchased feeds	4528	2646	12,277	11,149	371	*	***	NS
CP (t) in purchased feeds	106	52	272	248	4.86	**	**	NS
EM (GJ) supplied by on farm feeds[a]	8435	10,619	15,174	17,222	558	*	**	NS
CP (t) supplied by on farm feeds[a]	79	138	125	160	6.73	**	*	NS
EM (GJ) supplied by on farm feeds[b]	8800	10,742	15,196	16,856	201	**	***	NS
CP (t) supplied by on farm feeds[b]	72	130	121	161	2.38	***	***	NS

NS, not significant; *, **, and *** significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$.
CP = crude protein, ME = metabolizable energy.
[a] Calculated as the difference between herd requirements and amount of CP (t) or ME (GJ) from purchased feedstuffs.
[b] Calculated by analyses on homegrown feeds.

have a surplus of manure and the nutrient value of manure often exceeds the crop N requirements, increasing the proportion of UAA cropped with alfalfa could result in a more efficient use of the N entering the system. This could improve the N mass balance and the EUE of the whole system (Ketterings et al., 2008), if a decline in N_2 fixation, similar to the amount of N added to the manure, were to take place (Phelan et al., 2015).

In DYN_FS, increasing the crop diversity and crop rotation complexity by increasing the proportion of UAA with alfalfa contributed to increasing the proportion of UAA that was not treated with agrochemicals (herbicides and insecticides). Weeds were suppressed effectively over all the years in both systems (data not shown), but the corn and sorghum in DYN_FS, which followed alfalfa after 3 years, received fewer or no herbicides, and no negative effect was observed on weed control. Moreover, no insecticide was used against such pests as the western corn rootworm (*Diabrotica virgifera virgifera*) or the European corn borer (*Ostrinia nubilalis*), and no negative effect was observed. This greatly contributed to reducing the overall potential eco-toxicological impact on non target organisms at the system level, with results that are in agreement with those of Deike et al. (2008), and Liebman et al. (2008). Almost all the load indexes were ten-fold greater for CONV_FS than for DYN_FS on both farms, and the frequency of application per hectare and the amount of herbicide and/or insecticide utilized to produce one unit of DM, CP or ME decreased for DYN_FS, compared to CONV_FS. These results are in agreement with data from Davis et al. (2012), who reported that weeds were as effectively suppressed in a 4-yr rotation (corn-soybean-alfalfa-alfalfa) as in a 2-yr rotation (soybean-corn), and that the herbicide inputs in the 2-yr rotation plots were 6–10 times higher, while the fresh water toxicity was 200 times higher than in the 4-yr rotation.

Another major goal of improving the environmental performance and reducing impacts of agricultural production is that of minimizing energy consumption, in particular the energy derived from fossil fuels (Deike et al., 2008) as well as that of increasing the efficiency of energy use (Alluvione et al., 2011). The implementation of a dynamic forage system allowed the total energy input per hectare to be reduced from 28.8 to 20.3 GJ/ha and from 20.7 to 18.3 GJ/ha per year, and the EUE to be increased from 9.7 to 13.2 and from 12.5 to 15.3, from CONV_FS to DYN_FS, on Farm 1 and Farm 2, respectively. The obtained values were similar to those of Alluvione et al. (2011), who, studying similar cropping systems with a 4-yr wheat-maize-soybean-maize rotation, reported average energy input values of 22.3 and 17.0 GJ/ha per year and an EUE of 7.8 and 10.2, for conventional management practices and integrated farming practices that followed European Regulations, respectively. Lin et al. (2017) reported similar reductions when an improved management was applied to a conventional arable farming system in Germany (by introducing high-yielding varieties and better N management), and they reported a reduction in the energy input from 14.0 to 12.2 GJ/ha, an increase in the energy output from 155 to 179 GJ/ha, and an increase of the EUE from 11.1 to 14.6. In the present experiment, the obtained advantages were principally due to the increase in UAA cropped with alfalfa, which greatly reduced the use of chemical N fertilizers and of pesticides, as well as the tillage frequency (from annual corn crop to 3-yr alfalfa) and the adoption of whole ear corn silage instead of dry grain, which contributed to directly reducing the fossil fuel used for the conventional hot air drying process. Nemecek et al. (2008) reported that the introduction of grain legumes into intensive crop rotations, together with a high proportion of cereals and intensive N fertilization, caused a substantial reduction in fossil fuel consumption. The main reasons for this was that a reduced amount of N fertilizer was applied and a greater diversification of crop rotation helped to reduce problems caused by weeds and pathogens and therefore to reduce pesticide applications.

The impact of climate change (global warming potential) on a forage system is dominated by carbon dioxide (CO_2) and nitrous oxide (N_2O), and is counterbalanced by the C stocking ability of the soil (Nemecek et al., 2008). When all the emissions and sources were accounted for, the differences between the two forage systems, in terms of overall net GHG emissions, expressed on a per hectare basis, were 17 and 3% lower for DYN_FS than for CONV_FS for Farm 1 and Farm 2, respectively. Utilizing the functional units of DM, CP, and ME, the comparison showed greater differences between the two forage systems. The dynamic forage system generated 24 and 10%, 30 and 13%, and 54 and 26% fewer emissions per t of DM, per GJ of ME, and per t of

CP in feed products than the conventional forage system, on Farm 1 and Farm 2, respectively. The observed reductions for DYN_FS, compared to CONV_FS, could be explained by the reduced use of N fertilizer, pesticides and fuel consumption, and by the lower fossil energy consumed for their processing, manufacturing and transport. On Farm 1, another contribution to the reduction in the global warming potential was derived from the lower N_2O of the overall system. This was due to the presence of a larger proportion of alfalfa on the farm land than on Farm 2, and is consistent with the results of Jensen et al. (2012), who reported that emissions of N_2O tend to be lower for legumes than for N-fertilized crops and pastures, particularly when relevant rates of N fertilizer can be avoided and the concentrations of soil NO_3^- available for denitrification can be reduced. Reckling et al. (2016) introduced a framework that was developed with the aid of experienced agronomists and environmental scientists, which consists of a rule-based rotation generator and a set of algorithms to calculate impact indicators. The framework was tested in Västra Götaland (Sweden) and Brandenburg (Germany) where cropping systems with and without legumes were compared, and the results showed that, in both case studies, cropping systems with legumes reduced nitrous oxide emissions with comparable or slightly lower nitrate-N leaching (Reckling et al., 2016). Zucali et al. (2018) reported that among the most common fodder crops (in single or double rotation) grown in Northern Italy, alfalfa showed the best performances concerning the impact related to the global warming potential, acidification, eutrophication and non-renewable energy use.

Exploratory analysis on the impact of the two forage systems on the soil carbon stocking capacity, made with the aid of the Carbon Calculator tool, showed that the dynamic forage system has a greater potential to store C in the soil than the conventional forage system, when considering mono-cropped corn (data not shown). These results are in agreement with the conclusion of Little et al. (2017), who reported that, over the long-term, an alfalfa silage based rotation had a greater potential to store soil carbon than a corn silage based rotation, though this potential was not enough to offset GHG emissions from dairy production, thus implying that only a limited impact on soil carbon was obtained from switching from one system to another.

By introducing legumes and double-crops over a large part of the UAA, and adopting optimized management practices, relative to cutting forages earlier and more frequently and conserving them through ensiling, the farmers also introduced more complexity into their planning and labor management. When evaluated on a per hectare basis, the dynamic cropping system required more labor (+7 and 6% for Farm 1 and Farm 2, respectively) than the conventional system. The results become more favorable when labor referred to the functional units, with a similar labor time being required to produce 1 t of DM and 1 GJ of ME, and a reduction of 40 and 20% in time being required to produce 1 t of CP for Farm 1 and Farm 2, respectively. Furthermore, the use of more than one forage source distributed the labor requirements more uniformly over the year. With the dynamic forage system, growing alfalfa and double-crop (corn-Italian ryegrass) on a great proportion of UAA, spring alfalfa planting, spring Italian ryegrass harvesting, six to seven alfalfa harvests, and a corn harvest led to several short peak labor periods. The conventional system, in which corn grain and silage are grown on almost all the UAA, involves two major labor peaks in spring for corn planting and late summer for corn grain and silage harvesting (Borton et al., 1997). Even if more labor was requested, the production costs for DYN_FS, were lower than those computed for CONV_FS, for all the considered functional units, thanks to the marked reduction in crop production inputs (N fertilizer and pesticides). Humphreys et al. (2012), examining the sensitivity of the profit margin to N fertilizers and milk prices, found that a grass plus *Trifolium repens* based system became more profitable than a N fertilized grass-only system, from 2006 onwards, especially as a result of the increased volatility of prices (Phelan et al., 2015).

5. Conclusion

On the basis of data gathered at a farm level, we have concluded that the here presented new dynamic forage system has the potential of being profitable and could enhance production efficiency and environmental quality in the more intensive forage systems adopted on dairy farms in the Po plain in Italy. The dynamic forage system was able to provide more ME and CP on both farms than the previous system, while a similar milk production and similar milk quality were maintained, although a slight decrease was observed in protein and in the casein content. Assuming similar trends in commodity prices to those of the last decade, this analysis indicates that the dynamic forage system will become an increasingly more profitable alternative to conventional corn based systems.

Furthermore, the potential environmental benefits of dynamic forage systems may be expanded even more by considering other ecological benefits, such as enhancing water quality, improving soil health, providing wildlife habitats and conserving biodiversity within crop fields and in adjacent habitats, all of which are aspects that have not been considered directly in the present paper.

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