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How to manage cows yielding 20,000 kg of milk: technical challenges and environmental implications

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ABSTRACT

The world cow milk production will reach between 810 and nearly 1,000 Mt in 2050, implying changes in dairy farm management as well implications in environmental impact, especially as far as greenhouse gases (GHG) emissions, and nitrogen and phosphorus excretions are concerned. The future dairy farms will need to become smarter, profitable, and high yielding to continuously improve the sustainability of milk production. Among western countries, the Italian dairy industry has good performances both for milk yield and quality. Most of its milk is used to produce highly exported PDO cheeses with high added value. It could represent a model to study the impact of accelerated phenotypic trend on technical and environmental challenges. Assuming a constant average increase of milk yield equal to the actual phenotypic trend (+128 kg per cow and per year), the production of the current best cows (20t/head year^{-1}) will become the average herd performance of the intensive dairy farms in 2030. Thus, maintaining the current Italian milk production (equal to 12.1 Mt), the higher milk production per head would cause a reduction of the environmental impact of 11.4% and 60.1% for GHG, 9.1% and 36.0% for N, 15.8% and 52.6% for P considering two scenarios of present phenotypic trend or 20t/head year^{-1}, respectively. To cope with this challenge, technical suggestions for breeding and feeding the 20t dairy cow are given.

HIGHLIGHTS

- Current top Italian cows represent the 2030 average of dairy herds
- Genomics and management will drive the productivity success
- Efficiency will reduce dairy environmental impact

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Introduction

Looking at the 'Future of food and agriculture', FAO (2018) developed three alternative scenarios projected to 2050 and '*designed to reflect various degrees of challenges for equitable and sustainable production within the challenges space*' (O'Neill et al. 2017): business as usual (BAU), stratified society (SSS) and towards sustainability (TSS). In all the scenarios, an increase in the cattle stock between 30% and 50% of heads is expected, with the larger expansion in the sub-Sahara African countries. Based on a linear and exponential projections of 48 years FAOSTAT (2020) historical data (Figure 1), in 2050 the world cow milk production (about 85% of the total milk produced), will be between 810 and nearly 1,000 Mt.

Such an increase in production will imply relevant problems of environmental impact, especially regarding green-house gases (GHG) emissions, and nitrogen and phosphorus excretions. Sustainable intensification is the main way to cope with this challenge (Pulina et al. 2017), as suggested for the most important crops and livestock productions (Balmford et al. 2018). Capper and Cady (2020) compared the emissions of the US dairy cow industry for the years 2007 and 2017, period in which an increase of +16% in total production was registered. A decrease of 20% for GHG, 17.5% for N, and 14.5% for P excretions was observed. The authors explained these results through the continuous increasing phenotypic trend of milk production that indicates an improvement in the

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efficiency of feed and energy use and that allowed to produce the same amount of milk with a smaller number of cows. The dairy farms of the future should become smarter, and high yielding and profitable as well continuously improve the sustainability of the dairy industry (Britt et al. 2018).

Among the western countries, the Italian dairy industry has good performances both for milk yield and for quality. The milk is mostly processed into highly exported PDO cheeses as Parmigiano Reggiano, Grana Padano and Gorgonzola.

The first purpose of this paper is to analyse the available data to design future national trend in milk production. A second goal is to provide technical suggestions for cattle management and feeding in the hypothesis that the current performances of the top cows and farms will becomes the standard average output of the Italian Holstein Friesian farms in 2030. A third goal is to estimate the environmental impacts of the Italian dairy system in 2030 under two productive scenarios designed for the Italian Holstein Friesian cow: one achieved projecting the current phenotypic trend and the other supposing that the actual best cows will become the standard.

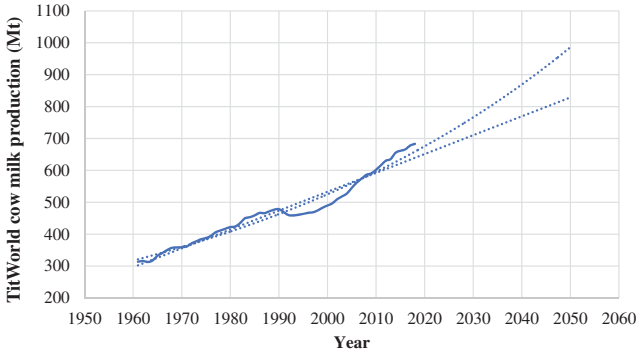

Figure 1. Linear or exponential projection of world cow milk production (dotted lines) based on historical trend (continuous line) (FAOSTAT 2020).

The Italian dairy industry perspectives

Since 1970, domestic demand for cow milk in Italy has required an increasing importation that passed from less than 60 Kt to more than 1.7 Mt in 1999. From that year onwards, the importation of raw milk has increased further, although with a lower rate, reaching a peak of about 2.0 Mt in 2011 (FAOSTAT 2020). Similarly, the export of whole cow milk has showed an increase since the 1990, but a lower rate compared to the importation. As a result of different import-export trends, the trading balance of whole cow milk has recorded a net importation of more than 1.1 Mt in 2017. Due to the increasing demand for cow milk, the national productive capacity has increased since 1970, with a steep incremental pattern in the period 1990–2000, but in the last two decades, the domestic milk production slowly declined until the milk quotas were abolished (2015), then it has been recovered and brought to the value around 12Mt, that represents the maximum national yield reached in 2000 (Figure 2) (FAOSTAT, 2020). During this period, the average production level per producing cow passed from about 3.8 t/y to about 5.8 t/y due to an increased global production of raw milk and a reduction of the number of cows, reaching the peak value of 7.05 t/y in 2018, just below the mean EU level of 7.28 t/y (Eurostat 2020).

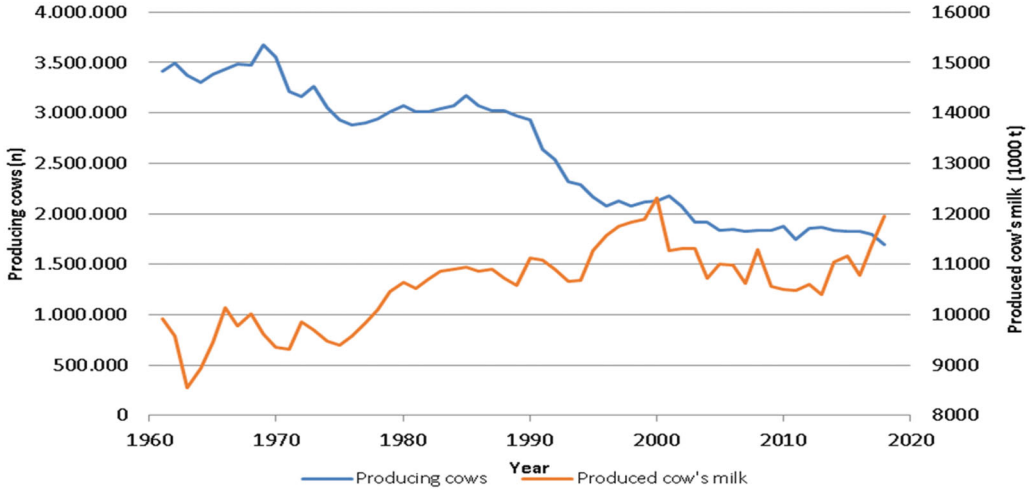

Figure 2. Graphical comparison between the official number of producing cows and the national raw cow milk production in Italy from 1961 to 2018 (data source: FAOSTAT 2020).

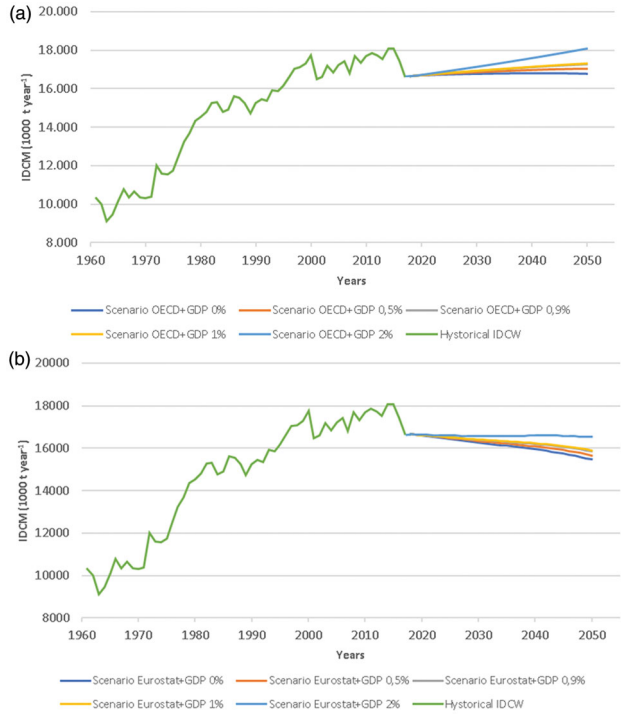

Figure 3. (a, b) Scenarios of the internal demand for the cow's milk (IDCM) with the OECD (2020) population projection (n) at different rates of national GDP change (€, current prices) till 2050. GDP: Gross Domestic Product.

The internal demand of cow milk (IDCM) of a country is reasonably related to the Gross Domestic Production (GDP) and to the number of resident people (Pop). Referring to the 1970/2017 period, the relationship between IDCM (as tons of milk equivalents (ME; CLAL 2020), Pop (OECD 2020) and GDP (FAOSTAT 2020) was described by a multiple linear regression (R^2=0.80) that has been used to build 10 possible future scenarios of IDCM in Italy until 2050. Scenarios were simulated by considering: (i) five rates (in %) of national GDP increase (€, current prices) with respect to the 2019 value: 0, 0.5, 0.9 (central value as suggested by Robinson 2015), 1, and 2; ii) two different 2050 population projections (*n*) according to OECD (2020) (Figure 3(a)) and Eurostat (2020) (Figure 3(b)) (63,546,400 and 55,859,640 units, respectively).

All scenarios showed a stable or declining trend in domestic milk consumption which suggests that the demand for domestic production may remain constant in the next decade and centred around 12Mt of milk. On this basis, simulated dynamics of the dairy cow population and of the environmental impacts were reported in the following paragraph.

The phenotypic trend of Italian Friesian and the performances of the top 100 Italian cows

The phenotypic trend of the milk production in the last 10 years of the Italian Friesian (contributing for over 90% to the total milk deliveries) was equal to +128 kg/y per cow (AIA 2020). Applying this trend to each cow of the national dairy herd and targeting stable national milk deliveries (12.1 Mt as observed in 2018), the number of Italian cows will decrease from the current 1.7 million of heads to 1.4 million of heads in 2030 and the average milk production level will pass from 7.1 up to 8.7 t/y. Inspired by Britt et al. (2018) who have observed that '*top-yielding cows in the United States [...] produced during the last decade [...] 10 to 14 standard deviation (SD) units greater than the average yield per cow in 2014*', we took into consideration the top 100 Italian Holsteins for production level could represent the average herd of a future Italian farm. Britt et al. (2018) also forecasted average milk production in US will reach 20t/y of milk per cow in 2040 or 2030 by fitting the past trends of milk production improvements with linear or exponential functions, respectively. The same authors also concluded that production improvement will favour annual milk solids, which yields would double in 50 years, reaching about midway between linear and exponential extrapolations. This tendency is justified by the potential improvement of genetic trends boosted by the genomic selection.

Production records of 400 lactations of the top 100 pluriparous Italian Friesian cows in the period 2014−2017 were gathered from the database of the Italian Association of Animal Breeders (AIA, 2020) and were analysed as follows. Animals were classified into two groups according to their lactation length (Steri et al. 2009): standard lactations (SL, length < 390 DIM; $n = 197$) and extended lactations (EL, with length between 390 and 700 DIM; $n = 193$), respectively. The distribution of frequency of lactation length within the same group is reported in Figure 4. Performance statistics and single-way ANOVA between SL and EL for each productive and reproductive parameter (significant differences declared per $p < .05$) of the top 100 cows were reported in Table 1.

Total and daily milk yield were significantly different between lactation length groups ($p < .01$), whereas no significant differences were observed for milk yield at 100 days and milk composition. The similarity of the cumulative 100 DIM production between the two groups reflected the pressure of genetic selection on peak level and fat and protein content of the last decades (Pretto et al. 2012).

No significant differences were detected on age at first calving or parity among cows with extended or standard lactations (Table 1; $p > .05$). Despite the similar milk production in the first 100 days, differences in reproduction traits (Table 1) clearly show that the two groups of lactation length require different management strategies for the technical and economic optimisation of the herd. EL group showed larger time to first insemination (17 days lower, almost an oestrus cycle) and number of services per pregnancy compared to the SL cows, respectively (Table 1). These figures confirm that cows with extended lactations have more difficulties to get pregnant with subsequent longer calving intervals compared to standard lactation cows ($p < .01$). On the other hand, it can be also speculated that cows with delayed pregnancy could have more opportunities to show an extended lactation (Bertilsson et al. 1997; Bohmanova et al. 2009; Pollott 2011). Considering the average lactation length of the two classes (standard and extended) and an average minimum period of 45 dry days, calculated average days open should be approximately close to 100 and 240 DIM for cows with SL and EL cows, respectively. These figures highlight that cows with EL should have a different management than SL cows, with postponed insemination aimed at taking advantage of their natural persistency of lactation (Manca et al. 2020).

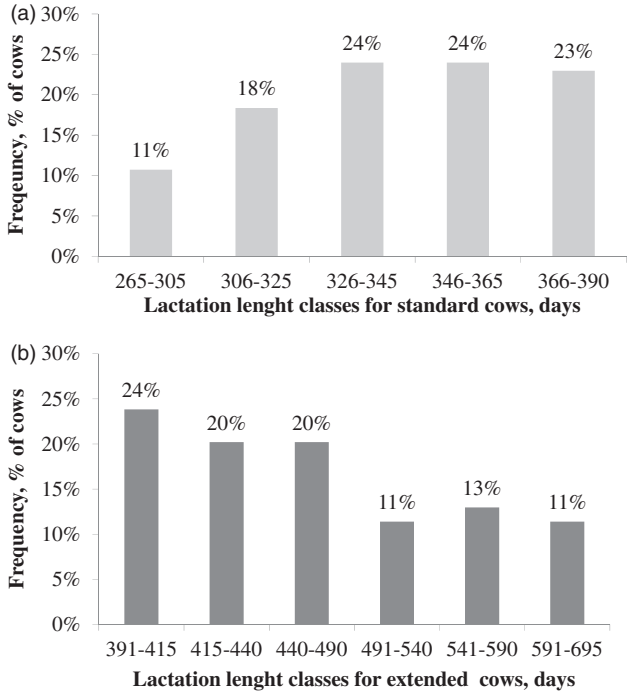

Figure 4. Distribution frequency of the lactation length of the top 100 Italian dairy cows in the years 2014–2017 (4 years, $n = 400$).

Table 1. Performance statistics for the Standard Lactation (SL, DMI < 390, n = 197) and Extended Lactation (EL, 390 < DMI < 700, $n = 193$) groups of cows reared in the top 100 Italian dairy cow farms in the years 2014–2017 (4 years, $n = 390$).

Variable	Group*	Mean	SD	25th percentile	75th percentile
Lactation length, days	SL	341.4^{B}	28.3	321	365
	EL	479.9^{A}	78.6	416	538
Milk yield, kg per lactation	SL	20065^{B}	1284	19053	20950
	EL	25166^{A}	3048	22731	27133
Average daily milk yield, kg per cow	SL	59.77^{A}	3.05	56.97	70.86
	EL	52.44^{B}	4.01	50.95	61.02
Milk yield in first 100 days, kg	SL	6742	640	6301	7076
	EL	6760	580	6293	7113
Milk fat, kg	SL	684.9^{B}	114.5	604	753
	EL	851.4^{A}	167.7	739	949
Milk protein, kg	SL	619.9^{B}	61.3	579.2	660.8
	EL	799.7^{A}	134.7	711.6	867.2
Milk fat, %	SL	3.42	0.53	3.09	3.68
	EL	3.38	0.45	3.04	3.63
Milk protein, %	SL	3.09^{B}	0.23	2.93	3.24
	EL	3.17^{A}	0.24	2.99	3.32
Age at first calving, months	SL	26.0	2.8	24	27
	EL	26.7	4.9	24	28
Parity, n	SL	3.26	1.11	2.0	4.0
	EL	3.15	1.03	2.0	4.0
Current lactation, number	SL	4.48^{A}	1.34	3.0	5.0
	EL	4.14^{B}	1.13	3.0	5.0
Time to first insemination, days from calving	SL	87.7^{B}	38.4	65	97
	EL	104.6^{A}	63.7	64	115
Time to conception, days from calving	SL	140.2^{B}	61.7	103	157
	EL	272.6^{A}	94.2	199	327.5
Inseminations per pregnancy, n	SL	2.77^{B}	1.92	1.0	3.0
	EL	5.24^{A}	3.04	3.0	7.0
Intercalving, days	SL	435.6^{B}	63.7	392	469
	EL	496.9^{A}	79.4	443	546

*Standard lactations length DIM < 390, $n = 197$; Extended lactations length DIM 390–700 DIM, $n = 193$.
Different superscript between cow groups indicate significant differences for P < 0.01.

Table 2. Descriptive performance statistics of the top 100 Italian dairy farms in the years 2018 (AIA 2020).

	Herd size, n. of cows	Milk, kg/head per year	Fat, %	Protein,%	Days in milk, DIM	Average age at calving, months	Days open days from calving
Mean	140.9	13102	3.71	3.38	313	41	153
SD	114.6	502	0.33	3.29	7.9	8.9	28
Median	177.0	13614	3.67	3.47	305	41	167

The top 100 most productive Italian cows are basically raised in the 100 most productive herds (Table 2). The comparison between mean and median values shows that most of the herds has a yearly level of production about 30% higher than the national average and a longer interval from calving to first insemination (AIA, 2020), being the latter not correlated to individual total milk yield per year (linear $r^2 = 0.02$; P = NS). Assuming that 100 top cows producing 20 t/y of milk would be raised in the same single farm, their biological needs and production will describe the average performance of the farm. Within this hypothesis, the following paragraphs will describe managerial choices required to maintain these performances.

A current example of a similar herd, which also pictures the future intensive dairy farming, could be the Ever-green-view Farm LLC managed by Tom and Gin Kestell and Chris and Jennifer Kestell in Waldo (53093 - Wisconsin, USA) that in in 2019 has been nominated by the Holstein International's as the most influential of the last 25 years, for owning 353 cows that have produced more than 20000 kg of milk per year. In 2018, the herd consisted of 85 cows milked 3 times per day, with an average lactation length of 248 days in milk. The average production was 20,233 kg/y of milk per cow with 3.88% of fat, 3.09% of protein, $218*10^3$ somatic cell count per ml and 21.5 mg milk urea/dL. Average milk yield in early, mid and late lactation, were 60, 73 and 57 kg/d for first calving cows and 73, 87 and 55 kg/d for second calving cows, respectively. Dairy efficiency was almost equal to 2.0 kg of milk per kg of DMI (Woodford 2018).

High production farms face challenging managerial choices: genetic, nutritional, reproduction and housing are the most important aspects to prioritise (Britt et al. 2018).

Genomics of top cows

The huge advancements on DNA sequencing technology have opened the genomic era for the dairy cattle industry. High-throughput Single-Nucleotide Polymorphisms (SNP) platforms allow the genotyping for tens of thousands of SNP markers, providing information for the implementation of genomic selection (GS) programmes. The GS allows for the early estimation of breeding values of bulls before entering the progeny test with high reliability, with a relevant reduction of the generation interval and a subsequent increase of selection speed. In US Holsteins, a reduction of generation interval in the path sire of bulls from 7 to 2.4 years has been observed (García-Ruiz et al. 2019). An interesting perspective of GS for the future dairy industry is the inclusion in the breeding goals of new traits that can counterbalance the negative effects of a high selection pressure on production (such as reproduction failure, negative energy balance, reduction of heat tolerance). Examples are health and reproduction traits, feed efficiency, and traits related to sustainability as GHG emissions (Weller et al. 2017).

One of the main concerns of intensive farming sustainability is about the use of drugs for controlling diseases such as mastitis and metritis. Apart from the direct costs represented by production losses caused by the disease, a serious problem is represented by the risk of increase of antimicrobial resistance. A recent simulation study by Kaniyamattam et al. (2020) suggested that a GS programme aimed at improving an economic index could be of help for reducing mastitis, metritis, as well as the antibiotic use.

One of the side effects of high selection pressure in favour of production traits is the loss of genetic diversity, which results in a reduction of the animal fitness, with negative consequence on longevity. This issue is enhanced in GS due to shorter generation intervals. The average increasing rate of inbreeding per generation in the Canadian Holstein population in the period 1990-2018 calculated using pedigree and genomic information was 0.75% and 1.05%, respectively (Makanjuola et al. 2020). However, if only the period of 2010–2018 is considered (i.e. the after the introduction of GS in 2009), inbreeding rates rise to values of 1.19 and 2.06%. This aspect should be therefore closely monitored in the future, being genetic diversity essential for the maintenance of adaptable cow populations and represent a resource for future market challenges.

Regarded from another perspective, genetic diversity is related to a possible biological limit of selection. The GS will favour the reaching of a plateau for the

Table 3. Diet reported for a dairy herd with a rolling average higher than 20'000 kg of milk per cows (estimated with the Ruminant Nutrition System; Tedeschi and Fox, 2018).

Diet feed composition (kg/d of DM)		Diet chemical composition	
Lucerne silage	7.0	Dry matter (DM)	50% of as fed
Maize silage	10.0	Crude protein (CP)	17.0% of DM
Grass silage	2.0	Rumen undegraded protein	49% of CP
High moisture Maize meal	4.9	NDF	29.5% of DM
Soybean meal	1.2	NDF from forage	23% of DM
Roasted Soybeans	2.5	Starch	28.5% of DM
Protein mix	0.8	peNDF	24% of DM
Molasses	1.0	Diet ME	2.69 Mcal/kg
		NFC	44.5% of DM
Total DMI	29.4	Fat	5.2% of DM

DMI: Dry matter intake; peNDF: physically effective NDF; ME: Metabolizable energy; NFC: Non-Fibrous Carbohydrates.

genetic improvement, due to the quicker fixation of favourable alleles. However, Weller et al. (2017) argued that two major genes for dairy traits detected in cattle, DGAT1 and ABCG2, still exhibit their polymorphisms in current dairy cattle populations, even though these variations are rather ancient. A possible explanation can be found in the fact that, for example, the allele of ABCG2 that increases milk yield has an opposite effect on milk protein content. Thus, changing the weight of the different traits in the economic index (e.g. Net Merit in US Holsteins) may turn the direction of selection with a resulting effect on the allelic frequency of the locus close to zero. Therefore, the realised reduction in genetic variability could be less than what expected.

The improvement of the ability of an animal to cope with climate changes will be one of the great challenges of animal breeding in the future. Heat stress tolerance is one of the most critical aspects for high producing dairy cattle, not only in tropical and sub-tropical but also in temperate climates. This issue is due both to the increase of temperatures and to the higher metabolic heat production in top producing animals (Segnalini et al. 2011). The selection for improving yield has impaired the ability of animals for tolerating heat stress due to the negative genetic correlations between these two traits. Tolerance to heat stress could be evaluated directly, using phenotypes such as rectal or intravaginal temperatures, or indirectly evaluating the effect of heat load on production performances. In general, the heritability of this trait is low, around 0.20 or less (Nguyen et al. 2016). Genomic breeding values for heat tolerance based on the production response have been calculated for Australian cattle (Nguyen et al. 2016). The genomic breeding values for heat tolerance exhibited favourable correlations with estimated breeding value (EBV) for fertility traits (ranging about 0.30–0.40) but unfavourable with most of production traits (from −0.90 to −0.20), thus confirming the antagonism between high production and environmental adaptation. The problem of such antagonism should be solved by using a measure of heat tolerance that is uncorrelated to production traits. Recently, a GS approach based in the use of Principal Component Analysis was able to derive a new index of heat tolerance for Italian Holstein bulls that is uncorrelated to other traits and has a heritability of 0.24 (Macciotta et al. 2017).

Finally, the implementation of genomic selection in the future dairy industry could enhance the positive effects of other technologies used in high producing cows like sexed semen, beef semen, and embryo transfer (VanRaden 2020).

How to feed 20t cows

A diet for Italian top 100 cows could be very similar to those used in dairy farms with lower production levels except that average DM intake would be close to 30 kg/d per cow. From a nutritional point of view, assuming that cows described in Table 1 could have 700 kg of BW, the estimated DMI based on their average production level using NRC (2001) equations, will result in 33.0 and 30.9 kg/d per head for the SL and EL groups, respectively.

Many aspects must be considered to support high yields with nutrition. Among them the priority should target (i) the forage quality of the diet. This aspect is currently considerable the most limiting factor, for its stimulating effect on feed intake and on nutrient supply. It allows to maintain the energy balance within adequate ranges to cover production requirements and to guarantee a satisfactory metabolic status; (ii) The fat, protein and mineral profile of the supplementation and (iii) the assurance of high standards of immunity and health.

A simulation made with the Ruminant Nutrition System model (www.nutritionmodels.tamu.edu;

Tedeschi and Fox 2018) allowed to reach DM intake of 30 kg/d and cover the energy and protein requirement of a cow producing 60 litres of milk, as described for the average animals of Table 3. The diet was formulated using high-quality forage (i.e. Lucerne hay and grass silage with a very low NDF of 40% and 50% of DM, CP of 21.0% and 16% on DM basis, respectively). The use of Maize silage with high digestibility and low lignin content (such as brown midrib corn) is also useful to reduce the total amount of undigestible fractions in the diet. Relative forage quality (RFQ) of 160-200 are suggested for high producing cows (Moore and Undersander 2002),

Feeds characterised by high ruminal degradability and low lignin content should be used to maximise substrate fermentation and nutrient absorption. Straw and low digestible fibre should be avoided to reduce filling effects and intake depression (Wang et al. 2014). The key point of the ration formulation firstly relies in the maximisation of nutrient intake and forage digestibility (Oba and Allen 1999). A limited amount of nutrients should be provided with starchy grains due to their acidogenic effect. Otherwise a high amount of pelleted concentrates, (>6 kg/d per cow) independently from the carbohydrate source (starch or high digestible fibre) offered in automatic milking systems, decreased the time the rumen remained below 5.8 pH and increased DMI (Haisan and Oba 2020).

The most effective nutritional strategy is undoubtedly the use of high digestible forages including alfalfa in early vegetation stages (Palmonari et al. 2014; Mordenti et al., 2017) and early cut silages, haylages and hays (Tabacco et al. 2018). Independently from nutrient supply calculations it has to be considered that DMI and optimum ruminal equilibrium highly depends on the relationships among forage fibre digestibility and the intake of forage undigestible NDF (uNDF; Fustini et al. 2017). These authors have shown that formulating diets with a 55% of offered DM based on high-quality forages (Lucerne with 36.7% of aNDFom and 40.2% of *in vitro* NDF digestibility at 24 hours) it is possible to reach a DMI higher than 29 kg/d per cow with high nutrient supplies. Indeed, using dry TMR based on Lucerne forage source, the optimum uNDF should range between a maximum of 0.48% and a minimum of 0.40% of live body weight to avoid rumen equilibrium alterations. A particular attention have to be deserved to TMR particle size; indeed, diets with low content of physically effective fibre (peNDF) should maintain high proportions of NDF from forages (aNDFom> 24% on DM basis) to stimulate rumination and adequate rumen retention time of forage particles (Fustini et al. 2017). Furthermore, reducing or increasing grain particle size might also increase or reduce starch ruminal degradability rate, respectively (Gallo et al., 2018).

The most promising strategy for increase the feeding value of forages is improving fibre digestibility, CP, and NSC (Brummer et al. 2009) and the agronomical efforts are currently oriented on improving digestibility of feeds and in development of Maize, Lucerne and other forages that have less lignin and more sugars or starch (Bouton 2007). Martin et al. (2017) also stated that crops with reduced lignification will be the base of diets fed to highly productive dairy cows in the future. The same authors reviewed the most promising biotechnologies applied in feed production and use to support the future dairy feeding which include brown midrib mutants of Maize silage and Sorghum and pearl Millet which have improved cell wall digestibility and reduced lignin concentration stimulating higher corrected milk yields (Oba and Allen 1999; Oliver et al. 2004). Likewise, other Maize mutant containing less lignin-arabinoxylan crosslinking by ferulate ethers, with greater cell wall digestibility could support greater DMI and milk production when fed to dairy cows (Jung et al. 2011). In case of diets with a high supply of Maize silage, the quality of this ingredient should be assessed considering both chemical composition and fermentative quality (Gallo et al. 2014).

Future ration formulation programmes will contain legume forages producing condensed tannins in leaves or that have complementary polyphenoloxidase (PPO) activity and o-quinones or o-diphenols (i.e. engineered Lucerne or Red Clover) which reduces proteolysis, helps protect feed protein both during ensiling and in the rumen, and is expected to improving Lucerne protein utilisation and enhance efficiency of protein use by dairy cows (Martin et al. 2017).

Poliphenols and tannins have been demonstrated to be highly relevant to improve efficiency of protein and feed utilisation, to reduce methane emissions and to improve the quality of animal products both in large and small ruminants (Vasta et al. 2019; Correddu et al. 2020).

Fat supplementation of the diet should be foreseen for average herd milk production greater than 15,000 kg/y per cow. Formulations may be developed to use whole seeds for milk yield, SFA or calcium soaps for fat production, and calcium soaps, whole soybeans, and fish oil to stimulate reproduction functions in early lactation (Palmquist and Jenkins 2017), respectively. The same author stated that '*energetic efficiency of milk synthesis increases quadratically with*

increasing milk yield when fat is fed in amounts equal to milk fat yield since dietary fat is transferred to milk fat without the energetic cost of synthesis'. Optimum metabolic efficiency is achieved when dietary fat amounts to the 16% of ME intake. Milk yield higher than 50 kg/d is reached when dietary fat is about 18% of ME intake (Kronfeld, 1976 cited by Palmquist and Jenkins 2017). The same author reported that fat supplementation included in low NDF diets had a more favourable effect on milk yield and energy partition to mammary gland than when it is added to high NDF.

Moreover, fat supplementation should be accompanied by balanced of dietary aminoacids to provide enough mammary supply and to maintain protein yield. Guidelines for protein feeding have advanced from simple feeding standards for dietary CP to more inclusive nutrition models designed to predict supplies and requirements for rumen ammonia and peptides and intestinally absorbable AA (Schwab and Broderick 2017). The inclusion of these info on the nutritional practice will be fundamental to reach lower protein diets and increased efficiency of microbial protein synthesis (Schwab and Broderick 2017).

Micronutrient supplementation is very important for high yielding cows since the limiting effect of one single element might have detrimental effects on production performances and animal health. The effects of minerals and vitamins on cell regulation, immune function, and gene expression are being studied actively. Discovery of unknown functions and responses to vitamins and minerals will open new fields of study, which should eventually result in improved cow health and productivity (Weiss 2017).

Considering physiological stages, early lactation nutrition should be carefully considered in view of the risk of carryover of inadequate nutrition in subsequent phases (Jørgensen et al. 2016). In particular, peripartum diets have an extreme importance to maintain the energy balance in early lactation. Indeed, DMI prepartum should be maximised to favour glucose balance in early lactation (Drackley et al. 2005). The transition period, 3 weeks before to 3 weeks after parturition, is important for health, reproduction, production and profitability of dairy cows and is especially critic in high yielding cows. Periparturient diseases can result from ruminal problems due by excessive grain in the pre-calving or fresh cow diet, perhaps worsened by overcrowding, heat stress, or other stressors. It may include inflammatory responses in alterations of metabolism, occurrence of health problems, and impaired reproduction (Cardoso et al. 2020). The increase of metabolic and health diseases during the transition period is indicative of dysfunctional host immune defences due to impaired nutritional status and metabolism (Sordillo 2016). Monitoring of the inflammatory status in late pregnancy and early lactation (i.e. pro-inflammatory cytokines concentration, liver enzymes indicators, positive acute-phase proteins nitrogen species and other plasma indicators) will be fundamental to predict metabolic overloads and to avoid metabolic problems in the sequent stages (Trevisi et al. 2015; Mezzetti et al. 2020). Bertoni et al. (2008) proposed a liver activity index based on an aggregate of plasma biomarkers that help to identify cows under high risk of peri-parturition disease problem, and poor productive and reproductive performances in subsequent lactation. Mezzetti et al. (2020) highlighted the dry-off as a challenging phase to manage dairy cows' health and could depose for a relationship between dry-off and immune alteration that typically occurs around calving time. The same authors clearly showed that cows with higher milk yield at dry off had the worst condition in the peripartum, and this could probably be related to the deeper metabolic changes they faced at dry-off consequently to milking interruption and suggests to programme the dry off below 15 kg/d of milk. Overton et al. (2017) reviewed the most effective biomarkers of metabolic, inflammatory and oxidative status also indicating the most recent technologies allowing to measure and monitor helpful parameters in dairy cow management. They stated that the effect of genetic, nutritional, and management strategies on periparturient cow well-being cannot be assessed without appropriate tools for measuring metabolic health at both the individual and herd levels especially measuring these parameters from plasma and milk that have strong associations with economically important outcomes related to metabolic health in early lactation, such as disease occurrence, milk yield, and reproductive performance. Furthermore, markers of oxidative status can predict the cow stress and support nutritional choices (Invernizzi et al. 2019). Oxidative stress must be monitored separately since often it has no clear relationships with plasma NEFA or BHB, suggesting that inflammatory status can be altered without direct associations with indicators of energy metabolism (Overton et al. 2017). The performance of high producing dairy cattle can be optimised to a certain extent by supplementing diets with optimal levels of micronutrients with antioxidant capabilities (Sordillo 2016). Most vitamins and trace minerals are able to optimise immunity through their antioxidant capabilities and severe deficits in both macro- and

micronutrients as a consequence of reduced DMI and NEB have a pronounced effect on host defence mechanisms and health disorders in early lactation (Sordillo 2016). Thus, diet formulation should aim to limit total energy intake to requirements but also provides proper intakes of all other nutrients before calving to help lessen the extent of NEB after calving (Cardoso et al., 2020).

Nutrition in unproductive phases (early life, growing and dry periods) should be also taken into account considering direct consequences and indirect effects of metabolic programming. Epigenetic effects of nutrition are included in the cut edge of nutrition studies and allow setting the metabolic conditions to better express the animal productivity potential. Nutrition in growing and pregnancy, especially when animals are raised under stressful conditions (i.e. heat stress) has been observed to induce permanent influence on animal productivity (Tao and Dahl 2013).

How to manage a 20t dairy farm

The herd reproduction management should consider individual evaluation of cows for their insemination whereas cows that have low conception rates are treated with embryotransfer (Woodford 2018). The voluntary waiting period should be decided individually. Thus, an early prediction of lactation persistency could be fundamental to manage the optimum insemination time for each individual cow, with economic benefits for the farm (Inchaisri et al. 2011). Manca et al. (2020) developed a discrimination criterion to estimate the lactation persistency for each cow at 90 DIM with a relatively small error (12% of cows).

The farm management does not include only genetic, nutrition and reproduction. In addition, calving and calves care, individual management of the cattle from their birth to culling, high turnover of the animals with low involuntary culling (<7%), cow comfort, and very high standards and consistency of farm operations are the basis of a rationale and effective management. Good practices are highlighted also in literature as fundamental for virtuous farms (Britt et al. 2018). Teamwork of the staff and information recording as support for the decision making is also suggested by the farmer as essential component of the farm conduction (Bewley et al. 2001; Durst et al. 2018).

Reproduction management should also consider effects of metabolic programming of nutrition and reproduction. Mossa et al. (2019) reviewed literature findings, showing how energy restriction in peri-conceptional period and gestation can impair cardiovascular development, reduce ovarian reserve and decrease cattle fertility. The same authors also hypothesised metabolic mechanism involving an hyperandrogenism induced by the nutrition level in cattle. Heat stress and can also affect these mechanisms (Succu et al. 2020). Thus, it could be speculated that persistent lactations and delayed inseminations could even counteract undesired effects of early lactation negative energy balance.

Comfort barns for high yielding dairy cows

Recently the loose housing system with cubicles in the resting area and with concrete walking areas is being thoroughly reconsidered, because of the 'technical' problems that this type of housing can cause to animals (Leso et al. 2020). Moreover, the consumer's ethical sensitivity is increasingly attentive to ensure that farmed animals have the chance to live a dignified life, as close as possible to that one they would have into the wild. Man, often unconsciously guilty of anthropomorphism, built farms deeming them suitable for cow's ethological and hygienic needs but often making great mistakes. Since many years, the herd replacement rate is about 30%, in most of cases for infertility, mastitis, and lameness (Compton et al. 2017). Many cows are not able to adapt to the breeding environment created by humans and this scarce adaptability is the first risk factor, and the aetiological factor, of these three 'syndromes'.

A barn suitable for accommodate 20t dairy cows must fully satisfy their ethology by removing all those structural and social factors that can inhibit its feeding and oestrous behaviours. In addition, the perfect barn for these cows must make possible to achieve the highest achievable hygienic and biosecurity standard, in order to eliminate transmissible diseases as important risk factors for the cows' functional longevity.

In March 2017 the web-magazine Ruminantia® presented a livestock managerial model called StallaEtica® (Ethical Barn®), a new way of handling and housing dairy cows in balance between social sustainability (farmer's income), environmental sustainability and respect of cow's right, with the aim of making cow's life dignified and very similar to that one they would have had in nature (Spinka 2006). It is a holistic approach that allows to manage dairy cows with very high productive performance minimising, as far as possible, stresses, sources of infection and environmental impact.

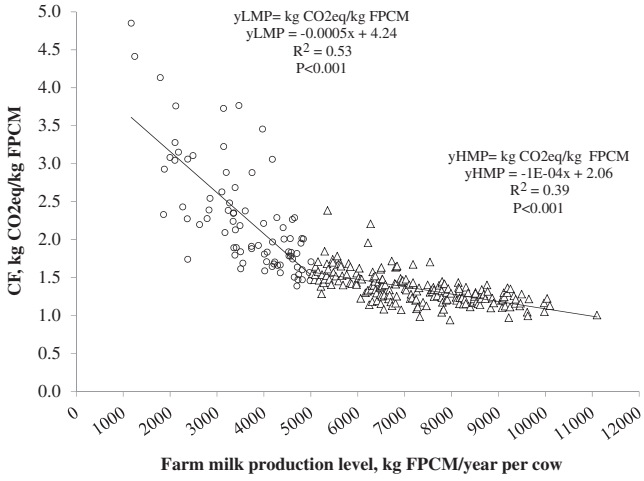

Figure 5. Relationship between CO_2eq emissions (kg of CO_2eq/kg of fat and protein corrected milk) and farm production level calculated on 282 Italian dairy farms (adapted from Serra et al. 2013) and divided between those with low milk production level (yLMP) and with high milk production level (yHMP).

The StallaEtica® for 20t dairy cows must be adequately equipped with cooling systems that prevent cows from 'getting sick' after heat stress. Vitali et al. (2019) clearly showed that climate might directly and indirectly impair the Italian dairy production performance due to increased risk of higher temperature and of reduction of precipitations. Thus, adequate strategies of heat stress prevention and mitigation within barns should be adopted. This is possible if the rectal temperature never increases more than 5 C° compared with the normal value, if the respiratory rate never rises above 80 acts per minute and if the ingestion does not drop when the THI exceeds 75.

The barn of the future is likely to be represented by the cultivated barn (Leso et al. 2020) where the wide resting area consisted of or only manure (compost barn) or of manure with the addition of organic material such as ground straw, rice husks, sawdust or coconut (compost-bedded pack barn). In both solutions the bedding material is aerated at least twice a day using a cultivator; this manipulation triggers an exothermic aerobic fermentation whose mainly function is to dry the litter. The air circulation within the bedding material inhibits the growth of all pathogenic anaerobic bacteria like Treponema (*Spirochaetacee*), which is the main aetiological agent of digital dermatitis, and the growth of many anaerobic bacteria involved in udder disease. The compost barn housing system provides a resting area of at least 17–20 m^2 per cow while the compost-bedded pack barn provides 10 m^2. The latter solution, also known as permanent litter, is 'cultivated' almost twice a day.

In compost barns, the large resting area is available for walking and only the feeding alleys are made of concrete. This allows the cows to fully manifest their ethology, that is, social interactions, play and oestrous behaviour. The presence of a such high level of animal welfare promote a significant decrease in fixed time artificial insemination, which requires the use of complex sequences of GnRH and PGF2α analogues. These routine 'medicalisations' are not well seen by consumers and if not well managed they can disrupt bovine hormonal patterns and genetic selection for functional traits.

Certainly, cultivated barns have a better environmental impact since the slurry stored and then diverted to biogas plants or fields is reduced compared to that produced in freestall barns with cubicles. In the resting area, urine and faeces are mainly subjected to an exothermic aerobic fermentation thus these dry by evaporation and not by percolation. The air circulation inside the bedding limits a lot the synthesis of methane which is mainly involved in the production of GHG coming from cattle farming.

StallaEtica® provides the possibility of a free access to outdoor paddocks and does not provide the systematic adoption of self-captures alongside the feeding alleys to make the animals' feed quiet and fear-free. This containment tool, useful for medical operations and artificial insemination, will be in an area downstream the milking facility that could be represented by automatic milking system (AMS) or milking parlour, towards which to direct the cows that need an intervention.

Environmental implication of 20t dairy cow

The increase of productivity is the main strategy to improve the sustainability of agriculture in general (Tedeschi et al. 2017; Tilman et al., 2011) and the dairy industry has been demonstrated to follow this rule (Capper and Cady 2020). To check the relationship between the delivered fat and protein corrected milk (FPCM; 3.5% fat, 3.1% protein) and carbonfootprint (CF) and nitrogen footprint (NF), a cradle-to-farm gate LCA study including a survey on 282 dairy farms on Southern Italy was performed, with a modified TIER 2 of IPCC 2006 (Cannas et al. 2013; Serra et al. 2013; Serra 2014). Results showed that the higher the milk production level of dairy herd the lower carbon footprint per unit of milk produced, with a breaking point around 5t of milk yield per cow (Figure 5).

Using the equation for the highest production levels and applying it to the entire Italian dairy sector, it

Table 4. Predicted reduction in CO_{2eq} emissions and Nitrogen and Phosphorus excretions by high yielding cows in 2030 in comparison with actual cows in 1990.

Year	Milk/y per head (kg)	Italian milk yield (t)	Concentration (g/kg of milk)	Total (t)	%
Carbon footprint					
1990	4,210	11,120,700	2,135	23,744,986	100
2018	7,136	12,084,030	1,346	16,269,643	69
2030*	8,672	12,084,030	1,193	14,413,536	61
2030**	15,307	12,084,030	0,529	6,395,865	27
Nitrogen excretion					
1990	4,210	11,120,700	21.9	243,810	100
2018	7,136	12,084,030	15.2	183,817	75
2030*	8,672	12,084,030	13.7	165,298	68
2030**	15,307	12,084,030	9.6	116,483	48
Phosphorus excretion					
1990	4,210	11,120,700	3.2	36,056	100
2018	7,136	12,084,030	2.3	27,518	76
2030*	8,672	12,084,030	1.9	23,096	64
2030**	15,307	12,084,030	1.1	12,828	36

*Current phenotypic trend; **20t milk production level for the high yielding dairy farms.

appeared that in 2018 the overall emissions of CO_2eq decreased by 31%% compared to 1990. With the same production of 2018, in 2030, these will further decrease by 8% if the current phenotypic trend is considered and by 42% if the average of the best farms will reach the 20t of milk per head (Table 4).

Highly productive dairy cows and rapidly growing heifers are more efficient than low productive/growing animals in N and P utilisation, hence decreasing the excretion of both elements per kg milk or kg body gain. The first reason for this higher efficiency is that maintenance requirements of N and P are amortised on a high quantity of milk or on a high growth rate. In order to have the first calving at 22 months of age, a good growth rate must be achieved. Zhang et al. (2016) found that a relatively low crude protein (CP) content of the diet (11.9% on DM) associated to a metabolisable energy content of 2.47 Mcal/kg DM were adequate to obtain an average daily weight gain of 900 g in heifers of 9–11 months. For Hill et al. (2013) higher values of CP are to be preferred to obtain satisfactory growth rates in heifers: 20.5, 17.5, 15.5, and 13.5% on DM for <2 months, 2–4 months, 4 months-first insemination, and during the first gestation, respectively.

Huhtanen and Hristov (2009) in a meta-analysis study showed that diet protein content is the first factor to consider in order to increase the N utilisation efficiency. At the same time, the authors underline the importance of having a high content of readily fermentable carbohydrates and a low content of fibre in the diet to increase the efficiency of N utilisation. This is consistent with what found by Pirondini et al. (2015) and by Crovetto and Colombini (2010), with less urinary N with diets high in starch, and lower N excretion in cows fed diets with a high (>1.8) dietary 'starch/crude protein' ratio. Indeed, a high dietary nonfibrous carbohydrate content allows rumen microbes to get enough energy to convert ammonia and carbon chains into microbial protein, thus reducing the amount of ammonia absorbed through the rumen wall and reaching the liver to be transformed into urea and then sent by the bloodstream to the kidneys and to the udder to be excreted with urine and milk, respectively. Highly productive cows are more efficient in the utilisation of nutrients, N and P included. In comparison with the average dairy cow of 1990 reported by ISTAT (2020) and yielding 4,210 kg milk/year, a high genetic merit cow yielding 15,307 kg/y would permit in 2030 a N excretion of only 48% in comparison with that of 1990 (Table 4). For P the excretion in 2030, assuming the same improvement in milk production seen above, would be just 36% of the P excretion computed for 1990 (Table 4).

The higher milk production implies less environmental impact and more profitability

One of the output of the 282 Italian dairy farms survey (Cannas et al. 2013; Serra et al. 2013) was the founding that milk production level is the most important variable that allows intensive farms to reach the best ranking in terms of technical efficiency and economic performance, expressed in terms of income over feed costs (IOFC) (Atzori et al. 2013; Cannas et al. 2013). Data from Serra et al. (2013) were used to regress one indicator of economic performances (€of IOFC per cow per year) on two indicators of environmental performance (carbon emissions and nitrogen excretion) of the surveyed 282 Italian farms. From the elaboration of these data a strong negative relation was observed among these indicators. Herds that can reach an IOFC higher than 1,500.00 €/month per present cow were those with carbon footprint lower than 1.30 kg of CO_2

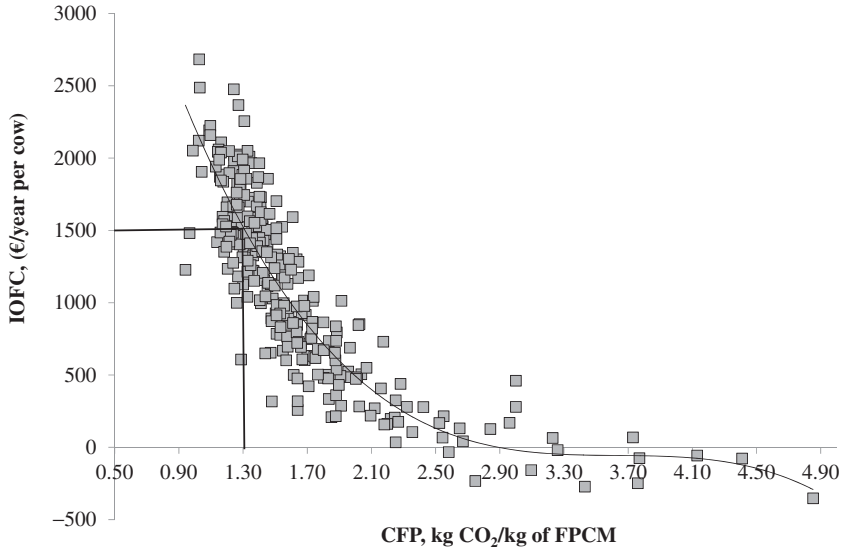

Figure 6. Economic vs. environmental performances of 282 dairy herds from Southern Italy referring to Carbon footprint (elaborated data from Serra et al. 2013; adapted from Cannas et al. 2013).

equivalents per kg of delivered FPCM (Figure 6) and a nitrogen excretion lower than 20 g/kg of delivered FPCM.

Conclusions

The future 20t cow is already among us. As in most of countries with a developed dairy industry, the Italian top producer cows overtake this threshold and most of the milk farms are likely to achieve an objective near this at the end of this decade. Genomic selection for persistent high-peak cows coupled with a voluntary delay for the first insemination at least 150 DIM are pushing to this goal that will require new feeding and breeding techniques to meet these biological and managerial challenges. High DMI, digestibility and palatability of the rations will be necessary, and it will be essential to design new stables to guarantee the right number of access to meals and an optimal rumination time. For this last aspect, cultivated barns, with their evolution towards an implant that can fully consider the cow welfare (StallaEtica®), seems to be preferable. High yielding dairy farms represent not only a viable solution to increase the environmental sustainability of the dairy industry, both decreasing their impact and leaving for natural restoration the land needed to produce the necessary feeds and forages, but they constitute the main way to satisfy the increasing demand for milk and dairy products forecasted for the next decades.

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Giuseppe Pulina ideated, coordinated the work and elaborated the world milk projections and the GHG impacts; Alessia Tondo provided and pre-processed the data of the most productive cows; Pier Paolo Danieli and Riccardo Primi elaborated the projections for the Italian milk market; Gianni Matteo Crovetto elaborated the projections for the N and P impacts; Alessando Fantini wrote the part StallaEtica; Nicolò Pietro Paolo Macciotta elaborated the genomic part and supervisioned the text; Alberto Stanislao Atzori processed the top 100 data and elaborated nutrition and reproduction strategies of the 20t cows and calculated the relationships among economics and footprints of milk production. What reported in this work is the responsibility in equal parts of all the authors. No conflict of interests was declared by authors.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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