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Management of "Modern" Holstein Cows Focusing on Sustainability and Resilience – Review of Recent Achievements

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Keeping Holstein cows requires a strategic approach that maximises milk production and promotes sustainability and resilience. As global demand for dairy products continues to grow, it is increasingly important to balance the development of the industry with environmental protection. Integrating genomics and targeted breeding strategies in dairy production can significantly improve sustainability and efficiency. Genomic selection uses deoxyribonucleic acid (DNA) markers and single nucleotide polymorphism (SNP) information to predict the genetic value of an animal, allowing breeders to select beneficial traits such as disease resistance, longevity, fertility, and feed efficiency. This not only increases productivity but also reduces environmental burden. Tailored breeding strategies can improve herd health and productivity and ultimately reduce the environmental footprint per unit of milk. Managing "modern" Holstein cows with a focus on sustainability and resilience means implementing practices that promote animal welfare, minimise environmental impacts, and ensure the long-term viability of the dairy farm. In the context of modern Holstein cows, the term modern refers to Holstein cows that have been selectively bred and managed using contemporary agricultural practices and scientific advancements. These practices include the application of genomics, precision breeding programs, advanced dairy cattle health care techniques, and updated herd management practices. Modern Holstein cows have been adapted and bred to meet the demands of today's dairy industry, considering factors like economic milk production, disease resistance, and environmental sustainability. The outcome of integrating genomics-targeted breeding and feeding strategies in Holstein cow management aims to enhance sustainability, productivity, and animal welfare, which would result in a more efficient and environmentally responsible dairy industry.

1. Introduction

The Holstein Friesian cattle is the dominant dairy breed in the world, including in Hungary, in terms of population number, level of production, and contribution to global milk production. Besides the advantages of intensive milk production using Holsteins, many experts and non-primarily experts criticise the sector for emitting greenhouse gases (GHG) and significantly contributing to global warming (Naranjo et al., 2020;). Numerous scientific works suggest that global warming, as a facet of climate change, represents a great challenge from a sustainability point of view (Peterson and Mitloehner, 2021). Several studies have indicated that livestock production, including transport, processing, and consumption, has a relatively large impact on climate change (Milani et al., 2011). According to the European Environment Agency (EEA), the EU-27's agricultural GHG emissions in 2021 were 378,430 kt CO_2 equivalent (eq.), 11 % of total emissions. Livestock accounts for 245,448 kt CO_2 eq. (64.85 %), of which cattle enteric fermentation is responsible for 155,937 kt CO_2 eq. (63.53 %) and manure management for 28,613 kt CO_2 eq. (11.65 %). In Hungary, the agricultural sector contributes 12.55 % of total GHG emissions (7,202 kt CO_2 eq.). Within this, livestock accounts for 3,506 kt CO_2 eq. (42.43 %), with cattle enteric fermentation constituting 1,966 kt CO_2 eq. (56.07 %) and manure management, adding another 591 kt CO_2 eq. (16.85 %). Extensive research and practical experience suggest that promoting sustainable milk production from this breed could play a crucial role in mitigating climate change. Therefore, it is essential to focus on the management of Holstein cows, ensuring their high-quality production remains sustainable for the

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future. This review aims to explore the key elements of sustainable management for Holstein cows, highlighting areas like genetic selection, nutrition, feed management, animal health, welfare, manure handling, waste management, energy efficiency, and water conservation.

2. Key Elements of Sustainability in the Dairy Sector

While many publications address the sustainability of intensive dairy production, the majority focus primarily on its impact on climate change. Although this impact is undoubtedly crucial, sustainability encompasses numerous other factors, some of which may be limiting. A more holistic approach to sustainability, considering multiple factors simultaneously, is needed.

This review seeks to explore various management elements contributing to the sustainability and resilience of Holstein cow milk production. By collectively addressing these elements, the environmental footprint of Holstein-based dairy operations can be further reduced. The key sustainable practices for managing Holstein cows discussed in this study include:

Genetic Selection: to balance production traits with factors like health, fertility, and longevity. Breeding programs should aim to develop cows that are adaptable to different environments, have good immune systems, and exhibit natural behaviours.

Nutrition and Feed Management: implementing sustainable feeding practices, such as incorporating locally sourced feeds, reducing reliance on imported feeds, and optimising ration formulations to minimise waste and environmental impact.

Animal Health and Welfare: Implement comprehensive animal health management protocols, vaccination programs, regular veterinary care, and preventive measures against common diseases.

Manure and Waste Management: implement effective manure management strategies, anaerobic digestion systems, composting, and nutrient management plans.

Energy Efficiency and Renewable Energy: Reduce the environmental footprint of the dairy operation by implementing energy-efficient practices. Optimise energy use in barns, milking parlours, and other facilities through efficient lighting, ventilation, and equipment.

Water Conservation: Implement water conservation practices, efficient watering systems, leak detection and repair, and responsible water use.

Knowledge Sharing: In the dairy industry, effective knowledge sharing is crucial for optimising production, enhancing sustainability, and navigating the evolving challenges and opportunities of the sector.

2.1 Genetic Selection

For a long time, the objective of genetic selection in the Holstein breed was to increase milk yield, butterfat, and protein. However, unfavourable genetic relationships among traits of great relevance to the industry (milk yield and fertility or welfare) have deteriorated some economically important traits, which has consequently motivated the development of more efficient breeding strategies for the increased long-term sustainability of the dairy cattle industry (Cole and VanRaden, 2018). Later on, the production aim was supplemented by conformation traits, with some functional traits such as longevity and calving ease (Brito et al., 2021). Together with intensive selection, the development of intensive dairy systems has been developed by innovations and technological breakthroughs, among which conventional genetic selection played a major role over the past decades (Miglior et al., 2017). Yet, the strong focus of the dairy industry on ensuring food security through higher productivity raises concerns about other sustainability dimensions (Clay et al., 2020). This situation requires a new breeding strategy, the simultaneous selection of productivity and functional traits such as adaptation, welfare, and resilience. Despite the major signs of progress in productivity, the long-term success of the dairy industry depends on the adoption of more sustainable breeding goals and management practices, especially from an agroecological perspective (Bito et al., 2021). The long-term sustainability of the dairy cattle industry depends on the development of balanced breeding goals to simultaneously improve animal health and welfare, productive efficiency, environmental impact, food quality and safety while minimising the loss of genetic diversity.

Genetic selection for some of these breeding goals has already been implemented around the world (Cole and VanRaden, 2018). Genetic selection is now based on a modern IT solution, DNA analysis and genomic breeding value estimation that allows us to make selection decisions not only on production, milk components (fat, protein), and functional conformation but also management traits with low heritability health and welfare, heat tolerance, adaptation and emission-related traits. The young animals could be genotyped at an early age, shortly after birth, pulling hair samples with follicles or even before birth using in vitro Embryo Transfer and embryonic cell biopsy techniques. The sampled DNA is analysed, and SNP information is used for calculating the Genomically Enhanced Breeding Values. This information provides a reliable tool for predicting their future performances in the dairy herd and can be used as a herd-size optimising practice to select or cull the given animals for dairy production. The minus variants could be inseminated with beef bulls, i.e., “Beef on Dairy” program, while others with higher genetic merits would stay in the farm to raise the genetic level of the whole herd, capable of higher milk production more efficiently, reducing the environmental impact of milk production per produced units of milk. The selection index is the Holstein Global Index, which, besides production traits (Fat and Protein), includes health and management traits such as Somatic Cell Count Score, Productive Life, Feet and Legs, and Calving Ability. It is estimated from the Breeding Value of the individual traits. This selection scheme could help to meet the requirements of sustainability and resilience. Holstein cows have been selectively bred for high milk production. However, focusing solely on milk yield can lead to challenges in terms of sustainability and resilience. It is important to balance production traits with factors like health, fertility, and longevity.

Breeding programs should aim to develop cows that are adaptable to different environments, have good immune systems, and exhibit natural behaviours. Genetic selection has also been a major driver in increased productivity, longevity, and efficiency of dairy cows, further reducing the environmental impact per unit of milk production (Pryce and Haile-Mariam, 2020).

HUNGENOM Project The National Association of Hungarian Holstein Friesian Breeders successfully runs a genomics-based selection scheme for participating Holstein Dairy Farms, the HUNGENOM project. It has 73 active herds, 52,975 DNA (hair)samples analysed since the start of this program in 2019 and published 51,165 Breeding Values that serve as a base for making breeding/culling or crossbreeding decisions.

2.2 Nutrition and Feed Management

Feeding dairy cows is an important factor from an economic and environmental point of view. Feeding strategies and methods are important tools for improving the efficiency of milk production, as well as the emission of greenhouse gases, in order to help sustainability and welfare. There are many promising opportunities for further reducing emissions and helping sustainability through feed and waste additives (Martin et al., 2017.) Nutrition of dairy animals has also allowed for a substantial improvement in production via the use of total mixed-rations (TMR) balanced for nutrient and energy requirements accounting for each animal's age and stage of lactation (National Research Council, 2001). More energy-dense or more digestible feedstuffs result in additional energy available to the animal and generate less CH_4 from fermentation (Knapp et al., 2014). An increase in the starch proportion of the diet, such as through an increase in concentrate levels, also results in a more rapid fermentation of these feedstuffs and decreased CH_4 production (Johnson and Johnson, 1995). Feeding higher starch diets requires increased grain production, which can cause additional consumption of fossil fuel and fertilisers that results in an increase in N_2O and CO_2 (Johnson et al., 2002); however, this system is usually offset by the substantial decrease in overall in CH_4 emissions (Lovett et al., 2006). Feeding of cereal forages can also favour propionate production and reduce CH_4 emissions due to the higher starch concentration (Beauchemin et al., 2009). Higher concentrations of legumes, such as alfalfa, when compared with grass forage-based diets, can also lead to an overall decrease in CH_4 emissions (McCaughey et al., 1999). Age of harvest of forage also has a significant impact on emissions, with advancing maturity resulting in more lignified and less fermentable substrate contributing to increasing emissions associated with higher ruminal acetate (Pinares-Patiño et al., 2003). In addition to alterations in forage or concentrate composition and ratio, supplementation of lipids to dairy cattle diets can also mitigate enteric emissions (Hristov et al., 2013 a). Replacing concentrates with lipids results in a decrease in fermentable substrate by the microbes in the rumen and can also decrease total protozoa and methanogen populations (Ivan et al., 2004). An inclusion of high-oil by-products, such as distillers' grains or oilseed meals, can result in decreased CH_4 emissions (Hristov et al., 2013b). Research on ensiled feeds in relation to enteric emissions is generally lacking, although it is anticipated that corn silage will mitigate emissions due to its higher starch content (Gerber et al., 2013). When directly comparing grass-versus-corn silage, a higher inclusion of corn silage seems to mitigate enteric CH_4 emissions (Doreau et al., 2012). There are many potential methods to mitigate enteric emissions through alterations to nutrition strategy and composition (Hristov et al., 2015). Optimal nutrition plays a critical role not only in GHG emissions but also in the health and productivity of Holstein cows.

2.3 Animal Health and Welfare

Consumers are interested in the safety and quality of dairy products (Drake, 2007). However, more recently, there has been increased interest in the care and housing of cows that produce milk and its associated products (von Keyserlingk et al., 2009). A fundamental condition for the production of large-quantity and high-quality milk is that the health and welfare of the cows must be adequate. The association between herd size, milk production level, health, and welfare is complex and affected by many factors Chapinal et al. (2014a), including the managerial skills of the farmer, rate of herd expansion, facilities, training and experience of personnel, and the ratio of caretakers to animals. Barkema et al. (2015) provided evidence that larger farms in both the United States and China have a lower prevalence of lameness, corroborated by Chapinal et al. (2014b). However, according to Anastácio et al. (2014), herd-level and within-herd prevalence of infectious diseases in general increase with increasing herd size (Wolf et al., 2014). This association may be confounded by recent herd expansion, including the purchase and mixing of animals from multiple sources, rather than being an effect of herd size itself. In many European countries, disease control programs have included the detection of DNA or antibodies in milk (Houe et al., 2006). Ensuring the well-being of Holstein cows is essential. Besides, the comprehensive animal health management protocols provide comfortable housing that allows for natural behaviours and promotes cow comfort, such as well-ventilated barns with adequate space, proper bedding, and clean water sources.

2.4 Manure and Waste Management

Holstein cows produce a large amount of manure, which can impact the environment if not managed properly. This waste is a significant source of N and P that, when land applied in excess of crop requirements, can cause contamination of surface water (Knowlton and Cobb, 2006). Excess N can also contaminate ground water through leaching. This poses a problem for human and animal health as consumed nitrate from drinking water is converted to nitrite in the digestive tract. One compound that affects air quality produced by dairy cattle is NH_3. Ammonia is produced when N in urea from the animal's urine reacts with urease present in manure (Place and Mitloehner, 2010). A substantial GHG produced by dairy cattle waste is methane. The amount of CH_4 emitted by dairy waste is dependent on the amount of carbon, hydrogen, and oxygen present in the waste, making manure storage, diet, and bedding major contributors to total CH_4 production (Place and Mitloehner, 2010). Implementation of effective manure can help capture and utilise the nutrients in the manure, minimise water pollution, and reduce greenhouse gas emissions.

2.5 Energy Efficiency and Renewable Energy

It was revealed that production growth is the dominant contributor to the increase of GHG emissions (Kim and Kim, 2012), while changes in the energy mix, especially the contribution of renewable energy sources, reduce the GHG emissions (Marques et al., 2019). To maintain high milk quality, including low bacteria counts, milk cooling ensures a raw milk temperature of around 3-4 °C. Cooling systems are major energy users. Data are reported from 6.4 to 33.4 Wh/kg milk for CM (conventional milking systems) and 6.4 to 38.7 Wh/kg milk for AMS (automatic milking systems) (Upton et al., 2013). Warm water is required for technological needs, such as cleaning milking equipment, materials and buildings. The main systems for water heating are electric boilers or boilers heated by natural gas. Data range from 3.3 to 22.8 Wh/kg milk for electric boilers measured in Finnish dairy farms by Rajaniemi et al. (2017). Appropriate lighting can improve productivity and safety on a dairy farm. The average values for the contribution of lighting to the total milking process were 1.4 Wh/kg milk (Shine et al., 2018) and 32.1 Wh/kg milk for incandescent lamps (Houston et al., 2014). Besides the unit operations mentioned above, a number of other electricity uses are common in dairy farms. Data for miscellaneous energy users range from 4.1 to 38,8 Wh/kg milk. Despite ample evidence in the literature for the positive effects of solar panels on reducing fossil energy use, there is only partial support for the hypothesis, stating that "Dairy farms using solar panels are more energy efficient" (Houston et al., 2014). However, as it is fossil-fuel-generated energy use that is most pivotal for reducing greenhouse gas emissions, the generation of solar energy proves to be an important measure to make the sector more climate-proof, although attention should also be paid to the rebound effects of solar energy use, which are reflected in an increase in overall energy use (Qiu et al., 2019). At the same time, it is very important to reduce the environmental footprint of the dairy operation by implementing energy-efficient practices.

2.6 Water Conservation

Water is used in many aspects of dairy production within dairy barns. The total water footprint of the dairy industry makes up 19 % of the global water use of all animal production, second only to the beef industry at 33 % (Mekonnen and Hoekstra, 2012). However, it has been estimated that the overall water footprint of milk production is 1 m^3/kg of milk (Mekonnen and Hoekstra, 2012). This represents a substantial amount of water that could be partially conserved throughout the production system on the farm (House et al., 2014). Robinson et al. (2016), based on their comprehensive study, came to the conclusion that free-stall dairy automated milking systems use more water on a daily basis than tie-stall and free-stall parlour operations. This leads to the reasoning that seasonality is a key factor in water use. Given that robotic facilities, which are becoming more common as milking systems, use a great amount of water, the industry should target efficient water-use strategies for these systems. Proper management of runoff and wastewater can also help prevent water contamination and protect local water sources.

2.7 Knowledge Sharing

To stay informed about sustainable practices, emerging technologies, and advancements in cow management, it is vital to engage with industry experts, researchers, and fellow farmers. Joining farmer networks or organisations dedicated to sustainable agriculture allows for sharing experiences, learning from others, and collaboratively pursuing sustainability goals. Agricultural exhibitions, meetings, and events organised by herd-book organisations and farmers' associations serve as excellent venues for exchanging valuable information.

3. Conclusions

Responsible Holstein breeding necessitates a holistic approach, entailing the coordinated management of numerous factors impacting sustainability. The balanced management of the various elements highlighted in this study can significantly enhance the sustainability and resilience of Holstein-based dairy production. The application of genomic information and genomic selection schemes can also enable cows to produce more milk from less feed, minimising environmental impact. These strategies, combined with selective breeding for enhanced animal welfare, can lead to healthier cows with longer productive lives. Although the advantages of these approaches might not be immediately evident, their integration into a thorough management plan can greatly enhance the enduring viability and success of dairy farming.

References

Anastácio S., Carolino N., Sidi-Boumedine K., Da Silva G.J., 2014, Q Fever Dairy Herd Status Determination Based on Serological and Molecular Analysis of Bulk Tank Milk. Transboundary and Emerging Diseases, 63, 293–300.

Barkema H.W., Keyserlingk M.A.G. von, Kastelic J.P., Lam T.J.G.M., Luby C., Roy J.-P., 2015, Invited review: Changes in the dairy industry affecting dairy cattle health and welfare. J. of Dairy Science, 98, 7426–7445.

Beauchemin K.A., McAllister T.A., McGinn S.M., 2009, Dietary mitigation of enteric methane from cattle. CAB Reviews, 4, 1–18.

Berry D.P., Bermingham M.L., Good M., More S.J., 2011, Genetics of animal health and disease in cattle. Irish Veterinary Journal, 31, 64–65.

Brito L.F., Bedere N., Douhard F., Oliveira H.R., Arnal M., Peñagaricano F., Schinckel A.P., Baes C.F., Miglior F., 2021, Review: Genetic selection of high-yielding dairy cattle toward sustainable farming systems in a rapidly changing world. Animal, 15, 100292, DOI: 10.1016/j.animal.2021.100292.

Chapinal N., Liang Y., Weary D.M., Wang Y., Keyserlingk M.A.G. von, 2014a, Risk factors for lameness and hock injuries in Holstein herds in China. Journal of Dairy Science, 97, 4309–4316.

Chapinal N., Weary D.M., Collins L., Keyserlingk M.A.G. von, 2014b, Lameness and hock injuries improve on farms participating in an assessment program. Veterinary Journal, 202, 646–648.

Clay N., Garnett T., Lorimer J., 2020, Dairy intensification: Drivers, impacts and alternatives. Ambio, 49, 35–48.

Cole J.B., VanRaden P.M., 2018, Symposium review: Possibilities in an age of genomics: The future of selection indices. Journal of Dairy Science, 101, 3686–3701.

Doreau M., Rochette Y., Martin C., 2012, Effect of type of forage (maize silage vs grass silage) and protein source (soybean meal vs dehydrated lucerne) in dairy cow diet on methane emission and on nitrogen losses. In: Hassouna M., Guingand N. (Eds), Proc. International Symposium on Emission of Gas and Dust from Livestock, 10-13 June 2012, Saint-Malo, France, 4.

Drake M.A., 2007, Invited review: Sensory analysis of dairy foods. Journal of Dairy Science, 90, 4925–4937.

Gerber P.J., Henderson B., Makkar H.P. (Eds), 2013, Mitigation of greenhouse gas emissions in livestock production: A review of technical options for non-CO_2 emissions, FAO Animal Production and Health Papers. 177, Food and Agriculture Organization of the United Nations, Rome, Italy.

Houe H., Lindberg A., Moennig V., 2006, Test strategies in bovine viral diarrhea virus control and eradication campaigns in Europe. Journal of Veterinary Diagnostic Investigation, 18, 427–436.

House H.K., Hawkins B.C., Barkes B.C., 2014, Measuring and Characterizing On-Farm Milking Centre Washwater Volumes. ASABE Paper, No 1908138, ASABE, 13-16 July 2014, Montreal, Quebec, Canada.

Houston C., Gyamfi S., Whale J., 2014, Evaluation of energy efficiency and renewable energy generation opportunities for small scale dairy farms: A case study in Prince Edward residential solar panel adoption. Journal of Environmental Economics and Management, 96, 310–341.

Hristov A.N., Lee C., Cassidy T., Heyler K., Tekippe J.A., Varga G.A., Corl, B., Brandt, R.C., 2013a, Effect of *Origanum vulgare L*. leaves on rumen fermentation, production, and milk fatty acid composition in lactating dairy cows, an inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production. Journal of Dairy Science, 96, 1189–1202.

Hristov A.N., Oh J., Firkins J.L., Dijkstra J., Kebreab E., Waghorn G., Makkar, H.P.S., Adesogan, A.T., Yang W., Lee C., Gerber P.J., Henderson B., Tricarico J.M., 2013b, Special topics – Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. Journal of Animal Science, 91, 5045–5069.

Hristov A.N., Oh J., Giallongo F., Frederick T.W., Harper M.T., Weeks H.L., Branco A.F., Moate P.J., Deighton M.H., Williams, S.R.O., Kindermann M., Duval S., 2015, An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production. Proceedings of the National Academy of Sciences, 112, 10663–10668.

Ivan M., Mir P., Mir Z., Entz T., He M.L., McAllister T.A., 2004, Effects of dietary sunflower seeds on rumen protozoa and growth of lambs. British Journal of Nutrition, 92, 303–310.

Johnson D., Phetteplace H., Seidl A., 2002, Methane, nitrous oxide and carbon dioxide emissions from ruminant livestock production systems, In: Takahashi J., Young B.A., Soliva C.R., Kreuzer M. (Eds), Greenhouse Gases and Animal Agriculture. Proceedings of the 1st International Conference on Greenhouse Gases and Animal Agriculture, Obihiro, Japan, 7–11 November, 2001, Elsevier, Amsterdam, The Netherlands, 77–85.

Johnson K.A., Johnson D.E., 1995, Methane emissions from cattle. Journal of Animal Science, 73, 2483–2492.

Keyserlingk M.A.G. von, Martin N.P., Kebreab E., Knowlton K.F., Grant R.J., Stephenson M., Sniffen C.J., Harner III J.P., Wright A.D., Smith S.I., 2013, Invited review: Sustainability of the US dairy industry. Journal of Dairy Science, 96, 5405–5425.

Kim K., Kim Y., 2012, International comparison of industrial CO_2 emission trends and the energy efficiency paradox utilizing production-based decomposition. Energy Economics, 34, 1724–1741.

Knapp J.R., Laur G., Vadas P.A., Weiss W.P., Tricarico J.M., 2014, Invited review: Enteric methane in dairy cattle production: quantifying the opportunities and impact of reducing emissions. Journal of Dairy Science, 97, 3231–3261.

Knowlton K., Cobb T.D., 2006, ADSA Foundation Scholar Award: Implementing waste solutions for dairy and livestock farms. Journal of Dairy Science, 89, 1372–1383.

Lovett D., Shalloo L., Dillon P., O'Mara, F.P., 2006, A systems approach to quantify greenhouse gas fluxes from pastoral dairy production as affected by management regime. Agricultural Systems, 88, 156–179.

Martin N.P., Russelle M.P., Powell J.M., Sniffen C.J., Smith S.I., Tricarico J.M., Grant R.J., 2017, Sustainable forage and grain crop production for the US dairy industry. Dairy Science, 100, 9479–9494.

Marques A.C., Fuinhas J.A., Tomas C., 2019, Energy efficiency and sustainable growth in industrial sectors in EU countries: A non-linear ARDL approach. Journal of Cleaner Production, 239, 118045.

McCaughey W., Wittenberg K., Corrigan D., 1999, Impact of pasture type on methane production by lactating beef cows. Canadian Journal of Animal Science, 79, 221–226.

Mekonnen M.M., Hoekstra A.Y., 2012, A global assessment of the water footprint of farm animal products. Ecosystems, 15, 401–415.

Miglior F., Fleming A., Malchiodi F., Brito L.F., Martin P., Baes C.F., 2017, A 100-Year Review: Identification and genetic selection of economically important traits in dairy cattle. J. of Dairy Science, 100, 10251–10271.

Milani F., Nutter D. and Thoma G., 2011, Invited review: environmental impacts of dairy processing and products: a review. J. Dairy Sci. 94, 4243–4254.

Moe P., Tyrrell H.,1979, Methane production in dairy cows. Journal of Dairy Science, 62, 1583–1586.

Naranjo A., Johnson A., Rossow H., Kebreab E., 2020, Greenhouse gas, water, and land footprint per unit of production of the California dairy industry over 50 years. Journal of Dairy Science, 103, 3760–3773.

National Research Council, 2001, Nutrient Requirements of Dairy Cattle. Seventh Revised Edition, The National Academies Press, Washington, DC, United States.

Peterson C.B., Mitloehner F.M., 2021, Sustainability of the Dairy Industry: Emissions and Mitigation Opportunities. Frontiers in Animal Science, 2, No 760310, 1–14.

Pinares-Patiño C., Baumont R., Martin C., 2003, Methane emissions by Charolais cows grazing a monospecific pasture of timothy at four stages of maturity. Canadian Journal of Animal Science, 83, 769–777.

Qiu Y., Kahn M.E., Xing B., 2019, Quantifying the rebound effects of residential solar panel adoption. Journal of Environmental Economics and Management, 96, 310–341.

Rajaniemi M., Jokiniemi T., Alakukku L., Ahokas J., 2017, Electric energy consumption on some Finnish dairy farms. Agricultural and Food Science, 26, 160–172.

Robinson A.D., Gordon R.J., VanderZaag A.C., Rennie T. J., Osborne V.R., 2016, Usage and attitudes of water conservation on Ontario dairy farms. The Professional Animal Scientist, 32, 236–242.

Shine P., Scully T., Upton J., Shalloo L., Murphy M.D., 2018, Electricity and direct water consumption on Irish pasture based dairy farms: A statistical analysis. Applied Energy, 210, 529–537.

Upton J., Humpreys J., Groot Koerkamp P.W.G., French P., Dillon P., De Boer I.J.M., 2013, Energy demand on dairy farms in Ireland. Journal of Dairy Science, 96, 6489–6498.

Wolf R., Barkema H.W., De Buck J., Slomp M., Flaig J., Haupstein D., Pickel C., Orsel K., 2014, High herd-level prevalence of *Mycobacterium avium* subspecies *paratuberculosis* in Western Canadian dairy farms, based on environmental sampling. Journal of Dairy Science, 97, 6250–6259.