Scotland's Rural College

INVITED REVIEW: Future directions for cow-calf contact research and sustainable on-farm application.

Whalin, Laura; Barth, Kerstin; Bertelsen, Maja; Bokkers, Eddie; Ferneborg, Sabine; Haskell, MJ; Ivemeyer, Silvia; Bak Jensen, Margit; Engelien Johanssen, Juni Rosann; Mejdell, Cecilie; Mughal, Mikaela; Neave, Heather; Vaarst, Mette; van Knegsel, Ariëtte T.M.; van Zyl, Coenraad; Wegner, Claire; Foske Johnsen, Julie

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Section/topic	#	Checklist item	Reported on page #
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	NA-neither
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	2-3
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	3-5
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	5
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	NA
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	NA
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	NA
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	NA
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	5-6
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	5-6
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	NA
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	NA
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	NA

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Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	5-6

Section/topic	#	Checklist item	Reported on page #
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	5-6
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	NA
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	NA
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	NA
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	6-29
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	6-29
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	6-29
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	NA
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	NA
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	6-29
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	6-29
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	29-30
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	30

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Interpretive summary

INVITED REVIEW: Future directions for cow-calf contact research and sustainable on-farm application. Whalin et al., Page 000 – 0000. There is increasing interest in incorporating prolonged cow-calf contact (CCC) into dairy systems, and evidence-based solutions are needed to guide farmers and legislation. Already there are research efforts to understand animal health and performance, methods for weaning and separation, foster cow systems, and opportunities for positive animal welfare in CCC systems. With refinements, CCC systems present an alternative dairy practice that could align with governance, social, economic, and environmental sustainability goals.

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ABSTRACT

Prolonged cow-calf contact (CCC) is of growing significance to the dairy sector due to increasing societal interest, implementation of CCC on farms, and research efforts. Incorporating CCC into dairy systems may be a polarizing change for academics and farmers.

However, by considering the challenges with curiosity, including those mutual to CCC and non-CCC systems, there may be an opportunity to collectively improve the management of dairy animals. The aim of this review was to describe current issues and constraints in CCC, propose opportunities to advance knowledge of CCC, and inspire forward-thinking questions for dairy systems. There are known challenges for CCC implementation, such as research reproducibility (e.g., suitable controls, validity types), and on-farm application (e.g., farmer perspectives, policies and corporate standards). To facilitate practical solutions for farmers wanting to adopt CCC we need research describing the effects of CCC systems on animal health and behavior. Already researchers have begun to explore cow and calf performance and health, methods for decreasing stress at weaning and separation (e.g., duration of contact, gradual weaning), foster cows, and opportunities for positive animal welfare in CCC systems (e.g., affiliative and play behavior). However, because dairying takes place in a complex system, changes may affect different facets of the system's sustainability. We suggest that the development of CCC systems should happen in dialogue with stakeholders. Cow-calf contact is an uncommon practice in dairy systems and exists in different contexts; thus, there are many questions to address before advice can be given to interested dairy stakeholders. Perhaps, these CCC related questions are an invitation to contemplate how we want dairy systems to look like in 30 years.

Key words: Sustainability; animal welfare; dairy systems; cattle

INTRODUCTION

There is increasing societal interest in the welfare of farm animals (Alonso et al., 2020), and a topic of growing significance to the dairy sector is prolonged cow-calf contact (CCC). Many people unaffiliated with dairy farming do not support the common practice of separating cows and calves at birth (Ventura et al., 2013; Busch et al., 2017), perhaps because they find it unnatural (Hötzel et al., 2017). To meet this concern, innovative farmers and industry leaders are beginning to support and implement various forms of CCC systems (e.g., Germany (Demeter HeuMilch Bauern: association of 40 organic, CCC dairy farmers marketing milk and meat according to IG Kalb und Kuh, which is a non-profit organization with a label for CCC on organic farms), Switzerland (Cowpassion: association promoting dam-calf contact systems, supported by a specialized consultancy unit), and the Netherlands (Kalverliefde: organic dairy collaboration of 7 farmers, heifer calf and cow together at least 2.5 mo, bull calf and cow together at least 35 d, premium price for milk and yogurt)). One survey of 104 CCC farmers from 6 European countries reported that 34% of these farms were dam rearing systems (i.e., physical contact and behavioral interaction between dam and her own calf), 12% were foster cow systems i.e., physical contact and behavioral interaction between a cow and an alien calf or calves), 28% used a combination of dam and foster cow systems, and 23% used initial dam rearing followed by artificial milk feeding (Eriksson et al., 2022; definitions from Sirovnik et al., 2020). This survey also found that farms varied in length of daily contact between cows and pre-weaned calves (46% full-day CCC (contact except during milking), 5% half-day (approximately 12 h/d) CCC, and 36% contact only around milking; Eriksson et al., 2022). With such different systems and limited research, it is no surprise that there are currently no common guidelines for farmers wanting to implement or already managing CCC on their farms.

Given the growing development of CCC, a common language, evidence-based solutions, and thoughtful questions are needed to guide those interested in system change. Sirovnik et al. (2020) developed common terms and definitions for describing CCC systems: these terms are used throughout this paper, and may be useful for future systematic searches.

Evidence-based solutions for managing dairy cows and calves together are beginning to emerge. Since 2019 there has been an increase in CCC publications related to dairy animals (Danyer et al., 2024). This research has explored topics such as responses to weaning (Wenker et al., 2022a; Bertelsen and Jensen, 2023a; Vogt et al., 2024a), calf behavior (Wenker et al., 2021; Bailly-Caumette et al., 2023; Bertelsen and Jensen, 2023b), milk production (Barth, 2020; Churakov et al., 2023; Sørby et al., 2024b), and affective states of CCC animals (Neave et al., 2023, 2024b). However, many questions remain relating to biological functioning, weaning and separation, opportunities for positive animal welfare, and, more broadly, CCC in the context of sustainability.

The development of societal, farmer, industry, and research interest may be perceived as a call for substantial change. Some stakeholders consider CCC as detrimental to animal welfare (e.g., Canadian dairy cattle veterinarians; Sumner and von Keyserlingk, 2018; New Zealand dairy farmers; Neave et al., 2022). Yet, when asked to consider the perspective of the cow, farmers have been reported to favor CCC systems (Mills et al., 2023). Perhaps the common practice of early separation is difficult for stakeholders to critique, and thus easily considered acceptable (e.g., shifting baseline syndrome; Mee, 2020). An overview of the challenges, with attention to overlap between CCC and non-CCC research movements, might allow us, as researchers and stakeholders, to consider future directions with curiosity, and collectively find better ways to manage the animals in our care. Given recent progress in CCC-related research, and the experience of the involved authors conducting these studies, the aim of this review is to describe current issues and constraints in CCC, propose opportunities to advance knowledge of CCC, and inspire forward-thinking questions for dairy systems.

METHODS

This narrative review originated from 2 in-person, CCC research meetings, held in December 2023 and April 2024. The first was a 2-day seminar in Norway celebrating the end of a 3-year CCC research project (SUCCEED, NRC) with a day of presentations, followed by a future-oriented discussion about CCC with research partners. The second was the fourth roundtable conference on CCC at the Thünen Institute of Organic Farming, Germany. This 3-day meeting consisted of short presentations of ongoing research in CCC and a reflection session on future research directions. All participants agreed that the effort invested, and ideas proposed in the discussions would be useful to the broader scientific community. Thus, notes from the meetings were sent to all participants, and everyone was invited to contribute to this review article. The authors of this manuscript have attended at least 1 of the in-person meetings, follow-up online meetings to work on the manuscript, and followed the Vancouver Convention's right to authorship. We did not conduct systematic literature searches, thus we may have missed some relevant articles.

Qualitative researchers often present reflexivity statements in their manuscripts to address their positionality (Jamieson et al., 2023). Given that societal concerns and values inspire CCC research, and our perspective and narrative approach to this manuscript, we felt that such a statement would bring greater transparency to our review. We are academics, ethologists, veterinarians, social and human scientists, animal scientists, physiologists, teachers, and mentors employed as graduate students, junior or senior scientists at research institutions and/or organic organizations in Europe and North America. We are interested in different aspects of One Health and One Welfare; animal health, production, and behavior; sustainability; and agricultural systems . All of us have experience in different facets of CCC research. We contributed to this review to continue enriching discussions, advance creative ideas for CCC in dairy systems, and ultimately make changes leading to a better world for humans, animals, and the environment.

CURRENT CHALLENGES IN CCC RESEARCH AND SYSTEM CHANGE ON-FARM

Research reproducibility

There are several on-going challenges in dairy cattle research that affect reproducibility. Here, we highlight 2 (i.e., use of suitable controls and validation) that deserve dialogue beyond this review to find solutions that will improve research design. Though CCC is the theme, we caution that these challenges are applicable to research questions in dairy systems in general.

Suitable controls

Many studies in extensive systems where cows and calves are managed together have been observational (e.g., Reinhardt and Reinhardt, 1981; Vitale et al., 1986). Not only are such studies difficult to reproduce (e.g., Voelkl et al., 2020), they may not be relevant for dairy animals with high genetic merit for milk production. For example, the early CCC papers followed beef cattle (e.g., Lidfors and Jensen, 1988), feral or semi-wild cattle (e.g. Vitale et al., 1986), or extensively managed zebu cattle (e.g. Reinhardt and Reinhardt, 1981). While these earlier studies provide fundamental information on cow-calf attachment, we also need research encompassing more intensive management systems, different housing and/or pasturing systems, daily milking routines and the continuation of lactation after weaning to better understand the effects of CCC on dairy animals.

Despite limitations for dairy management, the early studies highlighted unique social interactions between dam and calf (Vitale et al., 1986; Lidfors and Jensen, 1988; Veissier et al., 1990) and behaviors at weaning (Reinhardt and Reinhardt, 1981) that may be thwarted in most artificial rearing systems. To help contextualize these descriptive results for dairy cows, more recent studies have explored if cows value the opportunity to perform these behaviors by using preference and motivation tests. For example, dairy cows are motivated to access pasture as they would push high weights to gain access to pasture even when given free access to fresh feed inside (von Keyserlingk et al., 2017). Similarly, dairy cows managed with their calves would push high weights to reunite with their calves (Wenker et al., 2020; Jensen et al., 2024a) illustrating a high motivation of dairy cows to access their calves.

Currently, CCC is commonly compared with artificial rearing systems, where dam and calf are separated at birth and managed in different environments. In such study designs, it is difficult to disentangle confounding factors such as space allowance and feeding management. For example, compared to calves separated from their dam, CCC calves could have different durations of play either due to the presence of their dam, or the presence of more space (Waiblinger et al., 2020). As another example, though it is difficult to calculate how much milk calves will suckle from cows, when provided *ad libitum* milk, calves may consume 15 L/d (Borderas et al., 2009). Thus, results suggesting growth differences between calves raised in whole-day CCC systems compared to calves fed limited milk allowances (e.g., 10.5 L/d with either no or partial cow contact; Wenker et al 2022b) should be viewed in the context of this limitation. As a final example, the social bonds between the dam and calf are different in familiarity type and function than bonds between peer calves which may affect the level of social support provided (see review: Rault, 2012); perhaps the social behaviors calves perform are qualitatively different when in CCC systems versus when housed with peers. Therefore, system comparisons may be more appropriate for CCC studies than controlled experiments testing a single factor. Cow-calf contact research could progress to design studies where the control is also managed as a CCC system (e.g., full vs. part-time CCC; Bertelsen and Jensen, 2023a; Jensen et al., 2024).

Validity

Mason (2023) asks animal welfare research to become more rigorous by critically considering internal (ability to replicate), external (relevant to different contexts), and construct validity (avoiding circular reasoning by starting with a known indicator or a known situation). Cow-calf contact research to date can be critiqued for all of these validity types. First, behavioral (e.g., vocalizations, time spent suckling; Bertelsen and Jensen, 2023b) and cognitive (e.g., judgement bias; Neave et al., 2024) measures can be affected by the timing of observations. Perhaps future work could record behaviors over multiple days (Xiao et al., 2022) to assess differences more reliably. Second, many published CCC studies have taken place in controlled clinical trials in Europe (e.g., Hellström et al., 2023; Jensen et al., 2024; Sørby et al., 2024b). To be externally reliable, by attending to different farming practices and practical challenges, future studies may consider replicating published aims in commercial settings in different regions. Indeed, calf health research (Beaver et al., 2019) requires many animals (to ensure internal validity) and thus may need to take place on commercial farms over multiple years to ensure external validity (Dohoo et al., 2009). Additionally, some published CCC studies have included only a few groups (e.g., 2 groups; Johnsen et al., 2021, 4 batches; Sørby et al., 2024b; 4 groups; Johanssen et al., 2024); these sample sizes may limit our statistical inferences beyond these small populations. Though we should be cautious of small group sizes, we do see power in using them as hypotheses generators for future research if Type II errors are considered. Third, when proposing a welfare claim, it should be evident from the start of the study that either the valence of the indicator (e.g., allogrooming; Keeling et al., 2021) or the preference or motivation for the situation (e.g., cows are motivated to attain calf contact; Wenker et al., 2020; Jensen et al., 2024a) has been validated to avoid circular reasoning.

Given these prerequisites for validity, it can be time consuming (e.g., scoring behaviors) and costly (e.g., space needed for a CCC study) to capture valid data. There is ongoing development of automated systems (e.g., on-animal sensors, video recognition software, and sound detection tools) to monitor dairy cattle health (reviewed by Rutten et al., 2011) and welfare (reviewed by Costa et al., 2021; Stygar et al., 2021). Use of sensors could reduce the labor needed for the detailed monitoring of cow and calf activity, vocalizations, location, social proximity, and feeding behavior. However, these tools must be validated for precision and accuracy. Currently few sensors are externally validated for dairy cattle (14% in 2020), and we lack a common methodology for validation studies (Stygar et al., 2021). Also, even with valid sensors, we do not know if human observations may still be important for examining animals.

On-farm application

Incorporating CCC on-farm is not a simple task. Each farm system is influenced by the regional climate (e.g., average temperature and rainfall), environmental conditions (e.g., topography, space available), local traditions (e.g., areas known for cheese making, breeds commonly used), and country (e.g., issues raised in political discourse, economic and societal expectations for farming). These factors are largely out of an individual farmer's control. However, the farmer's attitude, knowledge seeking, willingness to implement change, and relationships with other stakeholders (e.g., veterinarians, nutritionists) are likely quite central to the success of system change.

Farmer and veterinarian perspectives

Farmers may perceive CCC differently depending on whether or not they already practice CCC. Non-CCC dairy farmers in New Zealand expressed concerns that CCC systems may cause challenges for mastitis management and colostrum intake, while also increasing workload (Neave et al., 2022). In contrast, existing CCC farmers perceived benefits to cow health and calf growth (Eriksson et al., 2022) with little concern for colostrum intake (Neave et al., 2022; Johanssen et al., 2023). Cow-calf contact farmers in Europe have also acknowledged that they spend less time feeding calves, and have even described a high work satisfaction (Eriksson et al., 2022; Johanssen et al., 2023). Non-CCC farmers have suggested that calves may become 'wild' if not milk-fed by humans (Neave et al., 2022). Yet, CCC farmers observed their calves to be more calm, confident, and social (Johanssen et al., 2023). These conflicting views regarding health, workload, and animal behavior might be related to context and individual preferences. Future work could clarify which pairings of contexts (e.g., space available) and management practices (e.g., milking system) allow for successful CCC implementation. Although one Canadian study found that the participating veterinarians believed that cow-calf separation helped to maintain calf health (Sumner and von Keyserlingk, 2018), we know little about how different agricultural stakeholders view CCC. We encourage future studies to describe these perspectives, as the social context may also play a role in CCC implementation.

Policy and corporate standards to consider

Jurisdictions approach standards of care for animals differently (Sandøe et al., 2023). Indeed, animal welfare/protection laws vary such that some countries have no or few codified regulations, and others only prohibit cruelty (Robertson and Sparks, 2022); thus, it is not surprising that there are few standards or laws regarding CCC. For example, the World Organisation for Animal Health (now WOAH, before OIE; 182 member states) acknowledges that cow-calf separation is stressful for all animals involved, and the European Food Safety Authority (EFSA) recommended in 2023 that calves and dams remain together 24 h postpartum and suggested that prolonged CCC should be increasingly implemented (Nielsen et al., 2023). To our knowledge, globally, there are no other industrial or legal regulations relating to CCC, and none requiring CCC during the milk-feeding period.

Without requirements or encouragements in terms of premium prices, farmers may only view CCC as costly. For example, as long as there is no minimum milk allowance for all calves, irrespective of system, feeding CCC calves might be considered more expensive than calves raised without cows. As previously described, calves may drink up to 15 L/d of milk when provided *ad libitum* access (Borderas et al., 2009), yet, in many countries, calves are fed 4 L/d of milk despite the numerous benefits of feeding calves a high milk allowance (reviewed by Welk et al., 2023). While it is unclear how future legislation and corporate codes will adapt to incorporate these systems, we stress the need to learn from stakeholders and animals to facilitate and support evidence-based and feasible solutions for dairy farmers wanting to adopt CCC. In the following sections, we will suggest opportunities to advance our knowledge of CCC.

FUTURE RESEARCH DIRECTIONS IN CCC

Biological functioning

Milk yield and udder health

Machine milk yield is the most emphasized dairy cow performance variable, and often saleable milk, and thus profits, are deemed 'lost' in a CCC system. We propose a few opportunities for further research. First, given that the milk suckled by calves in CCC systems is difficult to quantify, we need better models to encapsulate the CCC cow's performance. For example, delaying the first milk recording until after separation of the cow and calf can enable more reliable estimations of breeding values based on milk yield in CCC systems. However, this recording must be made by 95 DIM limiting the time of CCC (Spengler Neff et al., 2022). Also, given the potential carry-over effect of an increased pre-weaning calf gain on future performance, (Welk et al. 2023), a multi-faceted metric incorporating both machine milk yield and calf growth may provide a more holistic overview of performance in the system. Different challenges may arise also with this performance measure, for example in cases of illness impacting growth in the same manner as mastitis may impact milk yield (e.g., Costa et al., 2025). Furthermore, the transition to lactation is a well-known challenge in the life of dairy cows, which is associated with many production diseases in cows (Ingvartsen et al., 2003). Further research should address the possible positive or negative effects of calf contact on this period.

Second, as calves nurse approximately 8 times/d when cows are not milked (Kour et al., 2021), it is likely that CCC cows have milk removed more frequently than the traditional 2-3 times/d in parlors, or 2.7 times/d in robotic systems (Aerts et al., 2022). In early lactation, there is a positive relationship between milking frequency and milk production (Bar-Pelled et al., 1995), and the effect may last throughout the lactation (Hale et al., 2003; Wall and McFadden, 2007; Murney et al., 2015). A few studies have begun to quantify machine milk yield in the first 8-12 weeks after calving (Wenker et al., 2022b; Sørby et al., 2024b), 100 d beyond calving (Hanssen et al., 2024), or even the whole lactation (305 d, Barth, 2020; McPherson et al., 2024; Sørby et al., 2024a). The latter studies do not indicate the stimulatory effect of calf suckling on milk production in full contact systems. In systems that are more restricted, however, a stimulatory impact of calf suckling has been identified (Bar-Pelled et al., 1995; Fröberg et al., 2007). Future research should investigate if this discrepancy is due to length of CCC, poor udder emptying or other factors (e.g., local or systemic regulation of milk synthesis; reviewed by Wall and McFadden, 2012). There have also been several reports of incomplete milk ejection to the milking machine in CCC systems (Zipp et al., 2018; Johanssen et al., 2024; Rell et al., 2024) resulting in milk stasis, which reduces the survival of secretory cells in the mammary gland and thereby reduce milk production in the long term (Lanctôt et al., 2024). Future CCC research could explore management opportunities for poor milk ejection, the effect of udder fill prior to machine milking on udder emptying and milk secretion, and the effect of repeated lactations in a CCC system. For example, CCC cows with low machine milk yields may have a calf who is efficient at evacuating most of the milk, rather than a poor milk ejection, and methods are needed to distinguish these two cases from each other. We need further research regarding which cow characteristics (e.g., breed, individual differences in milk ejection) do well in CCC systems with machine milking.

Beyond milk yield, CCC may affect udder health. A systematic review (Beaver et al., 2019) indicated that CCC herds may have a lower risk of treating mastitis. Indeed, farmers practicing CCC perceive udder health benefits (Neave et al., 2022; Johanssen et al., 2023). However, a case report presented contrasting results such as calves spreading *S. aureus* and *Pasteurella multocida* in a foster cow system (Köllmann et al., 2021a). To address these contrasts, future CCC research could include a meta-analysis of SCC and an on-farm epidemiological study of udder health.

Calf growth and health

Research has begun to describe the growth and health of dairy calves in CCC systems during the milk-feeding period. Several studies have reported that dairy calves in CCC systems gain over 1 kg/d (Johnsen et al., 2021; Wenker et al., 2022b; Sørby et al., 2024c). Similarly, a systematic review reported that calves gain >1 kg/d when fed >12 L/d (Welk et al., 2023). Although milk allowance may be the most important contributor to ADG for the young dairy calf, it is not known if there is a maximum amount of milk a calf should receive. The literature is missing some descriptions of calf development in CCC systems such as rumen and microbiome development, skeletal growth, and metabolic health. We might start by exploring the methodologies used to describe how human neonatal growth rates during different periods in early life affect health outcomes (Kim et al., 2021).

Given the number of experimental animals needed for disease-related questions, little is known about the effects of CCC on calf health. Wenker et al. (2022b) reported that CCC poses a challenge for calf health, though CCC farmers perceive their calves to be healthier (Eriksson et al., 2022; Hansen et al., 2023). One opportunity for future animal health research is to take advantage of jurisdictions where individual animal health events are recorded. For example, in Norway a recording mobile phone app is being trialed on 10 CCC farms. The data from this app can be used for cohort studies and survival analysis to understand the causal relationship between CCC and calf health, and to answer questions such as; how does CCC affect cow health (e.g., udder health), and calf performance (e.g., feed intake, future fertility)?

Weaning and separation

Both CCC and non-CCC farmers acknowledge that weaning and separation are considerable challenges in CCC systems (Eriksson et al., 2022; Hansen et al., 2023). Indeed, a Norwegian study reported that animal stress associated with separation after prolonged CCC was the most common reason (54%) given by 213 farmers who had chosen to discontinue the practice (Hansen et al., 2023). Recommended weaning and separation strategies are needed for CCC to be a success.

The formation of the bond between the cow and calf begins within minutes of the calf's birth (Hudson and Mullord, 1977) due in part to neuroendocrine activity at this time (Mota-Rojas et al., 2024). In CCC systems with prolonged contact, the calf must go through the stressful processes of transitioning from milk to solid feed and achieving social independence from the cow (Weary et al., 2008). Behavioral indicators may be useful for understanding the stress. Vocalizations may facilitate social reinstatement between the calf and cow (Watts and Stookey, 2000) and communicate hunger (de Paula Vieira et al., 2008), or social dependence (Newberry and Swanson, 2008). For example, calves that could access milk from automated feeders after weaning showed reduced vocalizations compared with calves without supplementary milk, suggesting vocalizations may primarily indicate hunger (Johnsen et al., 2015a). Additional reported measures suggestive of a weaning program that promotes social independence include reduced searching behaviors of cows and greater distance between cow and calf (Johnsen et al., 2024; Neave et al., 2024a; Vogt et al., 2024b). An overlooked calf behavioral response to weaning is solid feed intake. A few CCC studies have indirectly measured feeding time (Bertelsen and Jensen, 2023b; Vogt et al., 2024a), or concentrate intake (Johnsen et al., 2021; Johanssen et al., 2024) and compared these to vocalizations to understand stress at weaning. However, these studies have not described the feeding development of CCC calves such as changes in solid feed and milk intake.

To date, a few approaches have been described for reducing weaning and separation stress of cows and calves in CCC systems, and each will be discussed in the following sections. These have been inspired by beef cattle research (see review: Enríquez et al., 2011), and include (1) the duration of daily contact before weaning is initiated (e.g., part-time versus whole-day CCC), (2) gradual weaning or ‘two-step’ methods that first remove milk then the mother (e.g., reduction of dam-calf contact; fence-line contact; nose flap), and (3) weaning age and duration (e.g. later versus earlier; longer versus shorter).

Duration of daily cow-calf contact during rearing

Duration of daily CCC during the rearing period affects social and nutritional dependence between cow and calf, likely affecting future weaning and separation responses (Meagher et al., 2019). Cows with part-time CCC (10 h/d) exhibited less searching behavior and had greater lying time on the day of separation and 24 h later compared with whole-day

CCC cows (23 h/d), but the vocal response to separation was similar (Neave et al., 2024a). However, calves with part-time CCC had a greater vocal response 24 h after separation compared with whole-day CCC, suggesting they may have experienced greater hunger after separation. A similar study (23 h/d versus 10 h/d of CCC) found no differences in the vocal and activity response of calves to weaning and separation (Bertelsen and Jensen, 2023a). In another study, Wenker et al. (2022a) found that calves with 7 wk of whole-day dam-contact showed more activity and less rumination before and shortly after weaning and separation than calves with partial dam-calf contact (physical contact, but suckling was never permitted). In all three of these studies, the calves were permitted to suckle pre-weaning, and had a behavioral response to weaning and separation. Though daily contact time may affect the stress at weaning and separation, there may be further methods to reduce this stress, which we highlight in the following sections.

Gradual weaning and separation methods

Gradual weaning in CCC systems should encourage calves to increase their solid feed intake before complete milk removal. While all weaning and separation methods create stress, abrupt weaning and separation after prolonged CCC is highly stressful for both cow and calf. Gradual weaning separates in time the removal of milk, nursing opportunity and cow-calf physical contact. In contrast, in abrupt weaning all of these resources are simultaneously removed.

One approach to weaning and separation is the gradual reduction of both CCC and milk intake; an example is reducing/restricting suckling to certain periods of the day (e.g. morning only) or a restricted number of hours (e.g. 2 h/d) (Neave et al., 2024a; Sørby et al., 2024c; Vogt et al., 2024a). Three publications compared this approach with another (abrupt weaning in Neave et al., 2024a; nose flap weaning in Vogt et al., 2024a; b), and found that vocalization frequency and searching behaviors were either greater or not different in the animals that experienced gradual reduction in dam-calf contact time. However, reducing the daily contact does not necessarily decrease daily calf milk intake (de Passillé et al., 2008). For example, when calves were restricted to 2 h/d of dam access, there was no difference in suckling time compared with calves with 10 h/d of dam access (Jensen et al., 2024c). A second approach is abrupt removal of milk, while maintaining full CCC; examples include nose flaps for calves (Wenker et al., 2022a; Vogt et al., 2024a) or udder nets for cows. The two studies examining weaning responses when using nose flaps found that calves showed reduced growth after weaning compared with calves who were weaned by a gradual reduction in dam-contact time or by fence-line approaches. There is also some early evidence that nose flaps may lead to injuries in the nose of beef calves (Valente et al., 2022; Kirk and Tucker, 2023) and thus should be avoided. Though some studies have managed CCC with udder nets (e.g., Johnsen et al., 2015a; Wenker et al., 2020), to our knowledge, no study has tested the use of udder nets to prevent nursing at weaning. This could be a non-invasive alternative, but is currently labor intensive (as milking systems currently do not accommodate udder nets).

Another approach involves abrupt removal of milk, while maintaining partial contact between cow-calf pairs; an example is the two-step fence-line method (Johnsen et al., 2015b; Wenker et al., 2022a; Bertelsen and Jensen, 2023a). It is difficult to find a consensus as the comparison method differed across all studies. However, fence-line weaned calves generally showed reduced stress indicators compared with the comparison group (abrupt weaning in Bertelsen and Jensen, 2023a; nose flap weaning in Wenker et al., 2022a; fence-line weaning with only auditory dam contact in Johnsen et al., 2015b).

A reverse approach involves maintaining milk intake via alternative sources after removal of CCC (Johnsen et al., 2015a; Sørby et al., 2024c). However, supplementary milk access may only convey a performance benefit at weaning for calves with access to supplementary milk throughout the rearing period (Johnsen et al., 2015a), perhaps because they are less nutritionally dependent upon the dam. An advantage of calves drinking from an automated feeder before weaning is that milk reduction is more controlled, which may be an opportunity to use individualized concentrate dependent weaning (Neave et al., 2019).

Finally, there is gradual reduction of both CCC and milk intake; an example is reducing/restricting suckling to certain periods of the day (e.g. morning only) or a restricted number of hours (e.g. 2 h/d) (Neave et al., 2024a; Sørby et al., 2024c; Vogt et al., 2024a). Three publications compared this approach with another (abrupt weaning in Neave et al., 2024a; nose flap weaning in Vogt et al., 2024a; b), and found that vocalization frequency and searching behaviors were either greater or not different in the animals that experienced gradual reduction in dam-calf contact time. However, reducing the daily contact does not necessarily decrease daily calf milk intake (de Passillé et al., 2008). For example, when calves were restricted to 2 h/d of dam access, there was no difference in suckling time compared with calves with 10 h/d of dam access (Jensen et al., 2024c).

Weaning age and duration

In CCC systems, calf age at weaning initiation and completion varies greatly among countries and between conventional and organic systems (Eriksson et al., 2022). To our knowledge, only two papers, from one system, have explored the effect of weaning duration (which was by design accompanied by different ages of weaning initiation; Johnsen et al., 2024; Sørby et al., 2024c). The authors tested weaning initiation at 4 wk of age over a 4 wk duration or initiation at 6.5 wk of age over a 10 d duration. The authors found that calves showed a more pronounced stress reaction (e.g., time spent near the separation barrier, vocalization frequency) to the 10 d compared with the 4 wk weaning duration, with no difference in the behavioral responses of cows (Johnsen et al., 2024), or the growth rate of calves (Sørby et al., 2024c). Future CCC studies could assess the behavior and performance of animals when weaning finishes at different ages. Additionally, ethical inquiries could clarify if it is better to have intense stress for a short duration, or medium stress for a longer duration.

In conclusion, further research is necessary to best guide how weaning and separation should be done in CCC systems. The beef literature (Enríquez et al., 2011) and the systematic review of positive effects of different weaning methods in artificially reared calves (Welk et al., 2024) could serve as a guide for strategically designing gradual weaning methods in CCC systems. For instance, weaning based on concentrate and roughage intake of the calf, rather than a fixed age, might benefit calf growth and reduce behavioral responses to weaning. The age at initiation of weaning as well as the weaning duration that is optimal in terms of stress reduction, health, cow (re)production and calf growth warrants further research.

Foster cows

In a sample of 104 European farmers, foster cow systems were used in combination with dam-contact (28%), or as the only CCC system (12%) a farmer used (Eriksson et al., 2022). In Denmark, farmers may choose foster systems due to the increase in saleable milk, use of undesirable cows (e.g., those with lameness or high SCC), and minimal infrastructure changes needed (Bertelsen and Vaarst, 2023). Similarly, some French farmers found that foster cow systems are a profitable option that may easily map onto pasture-based farms (Constancis et al., 2023). Put simply, foster cow systems may be a feasible approach to incorporate CCC into a farm (Bertelsen and Vaarst, 2023). However, even with limited research, there are challenges in foster cow systems. First, allosuckling (i.e., suckling of cows other than the foster dam) is an inherent behavior in this system, perhaps due to weak bond formation (Rosecrans and Hohenboken, 1982), especially if the foster cow was separated from her own calf months ago (Loberg and Lidfors, 2001). Allosuckling may transmit pathogens (including common respiratory pathogens), even if udder health may improve (Köllmann et al., 2021b).

As has been described, weaning and separation are challenging for CCC systems. Two studies have explored this topic in foster cow systems. Loberg et al. (2008) compared calves fitted with nose flaps for 2 wk before separation to calves who were abruptly weaned and separated. These authors found that calves weaned with nose flaps reacted less (i.e., less vocalizations and walking, and lower heart rate) at separation than the calves abruptly weaned and separated. Another approach for foster cow systems is to wean calves by removing foster cows, one at a time, from the cow-calf group. However, Jensen et al. (2024d) found that as each cow was removed, calves continued to suckle the same total duration, and subsequently competition and aggression increased in the group. Weaning and separation in foster cow systems may thus be particularly challenging for the smallest calves in the group (e.g., difficulties competing with larger pen mates wanting to suckle), and the cows remaining in the group (e.g., increasing calves/cow to nurse may lead to calves aggressively suckle and butt the udder).

In addition to the challenges described with the limited evidence available, we caution that foster cow systems may not be viewed as publicly acceptable (Sirovica et al., 2022). For example, a survey of North Americans found that people were negative towards systems involving dam-calf separation, regardless of whether the calves were housed individually, in groups, or with foster cows (Sirovica et al., 2022). Given the ethical reasoning underlying CCC related choices (Ventura et al., 2013; Hötzel et al., 2017), we encourage further work in social science and philosophy to clarify decisions relating to the future role of foster cows before we invest too much time and money.

Positive animal welfare with CCC as a model

Meagher et al. (2019) identified reduced abnormal behavior and improved growth as the clearest benefits of CCC for calves. However, there has been a growing interest in describing positive experiences in cattle. Although negative experiences are inevitable, minimizing negative experiences and enabling animals to experience predominantly positive affective states is a key to promoting positive animal welfare (Rault et al., accepted). Play, exploratory, social affiliative, and grooming behaviors are proposed to be rewarding for the animal (Boissy et al., 2007). A well-managed CCC system may facilitate these behavioral opportunities.

Affiliative social interactions

In addition to the provision of nourishment and protection, an important aspect of maternal behavior is affiliative behavior (Wenker et al., 2021), including grooming and maintaining close proximity (Newberry and Swanson, 2008), which may benefit both the cow and calf. A few studies have used these affiliative behaviors to better understand the importance of daily CCC duration. Part-time CCC systems are seen as more feasible due to more saleable milk than full-time cow-calf systems (Wenker et al., 2022b), but an important question is whether this management reduces the benefits for cows and calves. Bertelsen and Jensen (2023b) compared part-time (10h/24h) and whole-day (23h/24h) dam-calf contact and found that part-time contact calves received less maternal care (spent less time suckling and received less maternal grooming) compared with whole-day calves. Similarly, Jensen et al. (2024c) found that, compared to whole-day cows, part-time cows spent less time nursing and grooming their own calf. Therefore, recent studies indicate that reducing the daily duration of CCC may reduce the benefits of the maternal contact for the calves, but more research is needed to determine the length of daily contact time, and duration of CCC that accommodates affiliative social behaviors.

Maternal bond

The bond between the dam and her calf appears to be valued by the cow, regardless of the amount of time the 2 are together. One study suggested that the lack of difference in the amount of nursing in the inverse parallel position (suggesting a bond has formed; Waltl et al., 1995), and the probability of a cow nursing a calf other than her own meant that dam-calf bonds were similar in the whole-day and part-time systems (Jensen et al., 2024c). In support, there was no difference in maternal motivation 40 d postpartum (Jensen et al., 2024b), and when daily calf contact was reduced at 10 wk postpartum, the cows' motivation for full physical contact with their calf increased (Jensen et al., 2024a). Though one study suggested that the maternal bond was established even in the absence of nursing (Johnsen et al., 2015c), other groups have also reported nursing may be an important behavior for the dam as assessed with motivation tests (Wenker et al., 2020). To our knowledge we do not know how long the bond lasts, and future work may consider describing any changes in the maternal bond when pairs go from full contact to physical contact but no nursing, or no contact at all.

Play behavior in calves and cows

It is unclear if CCC alone positively contributes to increased play behavior in calves. Waiblinger et al. (2020) reported that calves reared by the dam performed more locomotor play than artificially reared calves; however, dam-calf contact was confounded with more space, which is likely the cause of increased locomotor play. The importance of space for locomotor play behavior was also evident in a study by Bailly-Caumette et al. (2023), where all calves played more when the dams left the pen to be milked. Interestingly, Bailly-Caumette et al. (2023) also found that, in addition to peers, the dams served as social play partners (social play defined as frontal pushing), while social play was never performed with an alien cow. Play, specifically mock fighting, between dam and calf has been described as an uncommon behavior in Boran cattle (Reinhardt and Reinhardt, 1982), but there is to the best of our knowledge only one other description of this is dairy cattle (Jensen, 2011). Future work on play behavior in CCC calves should thus take note of the role of the dam as a potential social play partner that may provide benefits beyond playing only with peers.

Development of competences and resilience

It has often been suggested that CCC calves are more socially competent than artificially reared calves, but there is little evidence to support this claim. An older study found that calves reared by the dam for the first 3 months of life achieved higher social dominance than artificially reared calves (Le Neindre and Sourd, 1984). Waiblinger et al. (2020) found that dam-reared calves initiated agonistic interactions more often and were receivers of interactions more often than artificially reared calves. Dam-reared calves received most of these agonistic interactions from cows other than the dam. In line with this, dam-reared calves (Buchli et al., 2017) displayed more submissive behavior towards an unfamiliar adult cow in a standard test, and dam-reared heifers tended (not statistically significant) to display more submissive behavior when introduced to the dairy herd (Wagner et al., 2012). Both studies above interpreted this as more appropriate social behavior. Studies investigating a broader range of behaviors in the home-environment (like the recent study on long-term effects of early social contact to peers; Clein et al., 2024) are warranted.

In a series of studies, Broucek and colleagues compared the learning ability of calves allowed restricted suckling of dam (after 3 d with dam, 3 × 10 min/d suckling until d 21), foster-reared calves (after 3 d with dam, reared by foster cows in group) and artificially reared calves (after 24 h with dam, separated and fed milk in teat bucket). When tested at 12 mo of age, foster calves were fastest to complete a labyrinth test (Hebb-Williams closed field test), artificially reared were slowest and dam reared were intermediate (Uhrincat et al., 2022). Cow-calf contact type and duration of contact were confounded, but this study suggests that learning ability in yearlings was superior in animals that had experienced extended contact, which in this study was foster cow contact. When the animals were re-tested in first lactation, these effects were not confirmed (Broucek et al., 2021a; b), highlighting the need to establish evidence of long-term effects of early cow contact on cognitive capacities.

Collectively, there are burgeoning efforts to document the opportunities to study aspects of positive animal welfare in CCC systems. Future studies could disentangle the confounding factors outlined in this broader section, as well as develop methods to understand the emotional valence associated with the described behaviors. As we progress our understanding of CCC as a system, we may also develop new indicators of positive states. Finally, we proposed a few opportunities to develop our understanding of the longer-term effects of CCC. As research in this area develops, these longer-term studies may help clarify if and how cows may experience the longer-term positive state, happiness, proposed by Webb et al. (2019). In essence, a good CCC system may be a step towards understanding what it is like to be a cow (e.g., Nagel, 1974) so that we may better accommodate their natural behaviors, as both calves and dams.

CCC IN THE CONTEXT OF SUSTAINABILITY

As described, there are animal-based research opportunities for us to work through before we can give advice for on-farm application of CCC. However, dairying takes place in a complex context where the physical environment, farmers' skills and dedication, and social expectations and regulations affect the practices employed. One approach to go beyond animal-based concerns could be to consider the sustainability of the system, that is, evaluating if the system meets today's needs without compromising future generations to meet their own needs (UN, 1987).

We will describe sustainability using the Food and Agriculture Organization (FAO, 2011) four pillars (Governance, Social, Economy, and Environment) in Sustainability Assessment of Food and Agriculture Systems (SAFA). Sustainable governance relates, among others, to corporate ethics, full-cost accounting, and planning for sustainable futures. These themes will often include levels higher than farm level (e.g., industry level), such as a dairy company establishing CCC systems to develop their vision and economic model. Full-cost accounting could also be achieved by considering both the potential income from milk, and meat from non-replacement calves, either at industry or farm level, as also addressed in economic sustainability below. Other themes in this pillar are educated and informed employees and transparent practices, which can be ensured at all levels (i.e., from farm to industry). The care and management of a CCC system require training and knowledge on animal health, behavior and human-animal relations (Johanssen et al., 2023). However, educational opportunities on CCC systems for farm staff are limited, and we encourage human research (e.g., anthropology, ethnography, agricultural education) to address this concern. Transparency regarding the type of CCC system used, and the length of time cows and calves spend together may also be relevant to the sustainability of CCC systems.

Social sustainability focuses on human and societal concerns, and is related to a dairy's social license to operate. It is worth noting that the sub-theme 'quality of life' presented in this pillar could be translated to animals, too (e.g., performing motivated behaviors, such as maternal care of calves). Improving the well-being of animals may simultaneously improve the well-being of the humans who care for them (Yeates and Main, 2008). For example, there is some evidence that humans who begin working in CCC systems recognize the animals engaging in natural behaviors (Neave et al., 2022; Bertelsen and Vaarst, 2023; Johanssen et al., 2023). In addition, a higher acceptability of the system and its products contributes to the social sustainability of CCC systems, though acceptability may sometimes conflict between consumer (price of the products) and citizen (norms and values) perspective (Verbeke, 2009). The social sustainability of CCC systems may be strengthened by incorporating attributes valued by citizens. For example, citizens value pasture access for cows (Hötzel et al., 2017) thus implementation of this practice may relate to social sustainability. Several groups have studied pasture-based CCC (Field et al., 2023; Johanssen et al., 2024; Sinnott et al., 2024). Calves born in cold and wet conditions (e.g., an Irish spring; Sinnott et al., 2024) are exposed to health risks, yet there may be behavioral benefits to raising calves in complex physical and social environments (Field et al., 2023). The impact of pasture access on social sustainability of the CCC system may depend on weather conditions affecting animal health. As another example, CCC dairy farm could extend lactations to avoid early separation, and reduce the number of calves born (Bolton and von Keyserlingk, 2021). Such a practice may increase the saleable milk produced on a CCC dairy farm (e.g., economic sustainability), and reduce the number of calves that may be transported off the farm to become veal (e.g., social sustainability). Though these examples address citizen concerns, future research may consider how other stakeholders (e.g., veterinarians) view the social sustainability of CCC systems. Additionally, to our knowledge, we lack instructive resources to guide farmers wishing to make system changes in the short- and long-term, nor do we know which systems can incorporate CCC (e.g., pasture access, agroforestry, ecosystem services) to better contribute to social sustainability.

Economic sustainability entails operations supporting long-term economic viability of the farm without compromising the social and environmental sustainability of the system (Elliot, 2007). More specifically, economic sustainability of CCC farms entails the ability of the farm to maintain solvency. The purpose of dairy farms is to produce saleable milk, thus a calf in a CCC system is in competition with this goal. Additionally, there may be costs associated with changes in workload and barn infrastructure, although many farmers report very modest investment (Hansen et al., 2023) and workload. One modelling study predicted that CCC systems are 1-5% more costly to run than an equivalent organic farm (Alvåsen et al., 2023). However, CCC systems may also offer economic benefits (Asheim et al., 2016) that warrant further study and modelling. Key areas for further study include animal health, calf growth, reproduction, future milk production, and premiums for CCC products (i.e., both milk and meat) to better understand their effect on the value chain.

Finally, environmental sustainability comprises aspects of emissions, energy, use of natural resources, biodiversity, and animal health and food safety (Hoffman, 2011). Life cycle assessments assess the ratio of the system's usable output (e.g., milk and meat produced) to the amount of GHG produced. These quantitative models have limitations because they do not take into account feed-food-fuel competition, and they poorly reflect the consequences of a system for animal welfare and society, but may help us understand important aspects of the environmental impact. One simulated model indicated that dairy CCC systems are 5-9% more environmentally challenging than non-suckling systems due to the reduced usable output (Mogensen et al., 2022). Similarly, extensive beef systems (i.e., pasture-based with CCC) may also emit more carbon/kg of output than intensive beef systems (Beauchemin et al., 2011). However, these calculations do not account for potential health benefits for CCC cows and calves, water use, management efficiency, or effects on biodiversity. Indeed, improved weaning weight and udder health can reduce GHG emissions (Özkan Gulzari et al., 2018; Mastert et al., 2019; Lancaster and Larson, 2022), and optimal grassland management can absorb carbon (Beauchemin et al., 2011). Taking into account the 'beef from dairy' systems, which may lead to better calf growth and health than current suckler beef models, will also be beneficial. Additionally, similar to our proposal in the section regarding milk yield, we encourage models to be developed to include calf weaning age and reduction of saleable milk yield (if conventional metrics are used), while fairly comparing environmental effects with conventional dairy systems.

CONCLUDING REMARKS AND QUESTIONS FOR FUTURE DAIRY FARMING SYSTEMS

Currently, CCC systems will not work for everyone. As with any change, the farm staff must be interested and invest in a change for it to be a success. With that acknowledged, we see CCC as an invitation for dairy farms to re-imagine themselves. The farming practices used to raise cows and calves together will continue to be as diverse as the farmers who use them. As we look forward, we, the stakeholders (i.e., farmers, veterinarians, researchers, advisors, teachers, and community members) have a creative opportunity to dream of what these farms could look like to better care for the environment, people, and animals that exist on a given farm. We anticipate farms in 30 years (2055) will look very different from farms of today due to changes in technology, environmental regulation, food production (e.g., synthetic milk produced in bioreactors by fermenting grass or other plants), consumer preferences, citizen attitudes, and animal health management, to name a few. These changes will raise important questions about balancing the interests of cows, calves, farmers, consumers, citizens and the environment. Deliberative, broad-minded, cross-disciplinary work will be needed to develop sustainable farming goals, which incorporates CCC systems.

Exactly what dairy farms of the future will look like or how CCC might be managed is unknown. However, we do know that there are important questions to research and discuss, regardless of CCC implementation, so that there are many evidence-based solutions for future dairy farms. We propose a series of questions (Table 1) that might be useful guides for those contemplating the future of dairy systems.

CONCLUSION

In conclusion, our review highlights the challenges and opportunities present in the study and implementation of CCC systems. Those studying CCC should provide clear reasoning for their choice of 'control' conditions and critically evaluate the validity of the methods. Those who promote CCC must continue to be in dialogue with farmers (both in support of and against CCC), and be aware of the changing political and economic incentives for different management practices. To support any future CCC farmers, we need research relating to health and performance, weaning and separation, foster cows, opportunities for positive animal welfare, and the four pillars (i.e., governance, social, economy, and environment) of sustainability.

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Table 1: The questions below reflect key knowledge gaps related to both dairy systems in general, and to cow-calf contact in particular, as identified throughout this review. These questions are invitations for us, the stakeholders (i.e., farmers, veterinarians, researchers, advisors, teachers, and community members), to contemplate.

Questions related to dairy systems in 10 years, 30 years:
1. Can on-farm technologies (e.g., animal-mounted sensors) be advanced to assess the welfare, behavior and performance of animals, or will human observations still be important?
2. What will farm staff development look like (e.g., education, participation in decisions, accommodating disabilities)?
3. How can the dairy sector and farmer create more integrated systems in the short- (e.g., calves as beef) and long-term (e.g., ecosystem services)?
4. What do we want dairy systems to look like?
5. How do we balance the interests between the cow, calf, farmer, consumer, citizen, and environment?
Questions specific to cow-calf contact in 10 years, 30 years:
1. What are suitable controls for CCC treatments in controlled experiments?
2. What could a well-managed CCC system look like in commercial settings in different regions?
3. Which contexts (i.e., both farm infrastructure, and stakeholders involved), and management practices (e.g., milking system) allow for successful CCC implementation?
4. How will future legislation and corporate standards incorporate CCC?
5. How can we better model a CCC cow's performance?
6. Which cattle characteristics excel in a sustainable CCC system (e.g., variation in milk ejection, breeds)?
7. How does CCC affect cow health (e.g., udder health), and calf performance (e.g., feed intake, body composition, future fertility)?
8. How can weaning and separation be refined to reduce separation stress and accommodate individual differences in calves' solid feed intakes?
9. How can we account for an animal's longer-term well-being (e.g., intense stress for a shorter duration versus medium stress for a longer duration; aspects of positive animal welfare potentially contributing to happiness)?
10. What, if any, is the future role for the foster cow system?
11. How does the behavior (e.g., affiliative and play), bond, competence and resilience develop when cows and calves are managed together?
12. Which systems can incorporate CCC (e.g., agroforestry, grazing systems, regenerative farming)?
13. How can CCC effects be incorporated across the value chain (e.g., one that takes into account male calves)?