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Dairy production in an urbanizing environment

A system approach in Bengaluru, India

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To life, resilience and empowerment

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Abbreviations

ADF	acid detergent fibre
BW	body weight
C_2O-eq	carbon dioxide equivalents
CH_4	methane
cMO	milk offtake corrected to body weight
CP	crude protein
D	dry cow
DM	dry matter
DMI	dry matter intake
DOM	digestible organic matter
DPS	dairy production system(s)
DPU	dairy production unit(s)
ECM	energy-corrected-milk
EF	enteric fermentation
FCE	feed conversion efficiency
H	mature heifer
L	lactating cow
LDH	productive dairy assets; incl. lactating and dry cows, plus mature heifers
ME	metabolizable energy
MMS	manure management system
MO	milk offtake
MW	metabolic weight
N_2O	nitrous oxide
NDF	neutral detergent fibre
P-FLOW, P-GEN	cluster predictor related to breeding
P-FOR, P-PAS	cluster predictor related to feeding
P-SSI	cluster predictor related to urbanization level
RUI	rural-urban interface
SES	social-ecological system
SSI	survey stratification index
THI	temperature-humidity index

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Summary

An urbanizing environment is typically dichotomized into agricultural production-oriented rural areas *versus* consumption-oriented urban areas, between which the flow of agricultural goods and services is a major linkage. Since agricultural producers and consumers are parts of the same social-ecological system that is getting more complex but also looser, the function of agricultural producers as a link between society and the environment becomes crucial. India is currently one of the fastest urbanizing countries. Its dairy sector supports the livelihood of about 70 million households and is the largest in the world. Numerous decades-long pro-poor dairy development programmes were implemented and boosted rural-urban linkages through milk flow. However, the current impacts of urbanization on dairy production are neither assessed in terms of structural change in the dairy sector, shifts in resources availability and use by dairy producers, nor in terms of the increasing complexity of the social-ecological systems that centres around dairy producers.

The present study aims to provide deeper insights into the impacts of urbanization on dairy production, taking the dairy sector of the Indian megacity of Bengaluru (10 million inhabitants) as case study. Since the 1970s, Bengaluru is one of the fastest growing cities in India and benefits from its own dairy development program, while (peri-)urban dairy production is common. The present study first focusses on identifying and characterizing the dairy production systems (DPS) that co-exist in the rural-urban interface of Bengaluru, while highlighting potential linkages between its social-ecological components. In a second step, the present study focusses on quantifying the impacts of distinct dairy production strategies in terms of resources use efficiency, namely feed conversion efficiency, and global environmental impact, namely the emission intensity of greenhouse gasses, in relation to the spatial distribution of DPS across Bengaluru's rural-urban interface.

To identify and characterize the DPS co-existing in Bengaluru's rural-urban interface, a dairy production baseline survey was conducted with 337 dairy producers across six urbanization levels. Four DPS were identified through a two-step cluster analysis based on five predictors: the urbanization level of the settlement, reliance on self-cultivated forages, use of pasture, cattle in- and outflows within the herd and share of specialized dairy genotypes. DPS-1 was ubiquitous and extensive, with cattle feeding not relying on self-cultivated forages but rather on public grounds for pasture and forages collection, or market wastes, or both; DSP-2 was rural and semi-intensive, with cattle feeding relying on both pasture and self-cultivated forages, and a breeding management of specialized dairy genotypes. DPS-3 was the same as DPS-2 apart for their breeding management, which did not rely on

specialized dairy genotypes. DPS-4 was rural and intensive with a feeding management relying on self-cultivated forages but not on pasture. Dairy producers in DPS-1 were typically landless producers and used mostly informal marketing channels to sell their milk, while those in DPS-2, DPS-3 and DPS-4 relied on dairy cooperatives for inputs and as marketing channel. Overall, Bengaluru's dairy sector had a well-established network of dairy cooperatives and was characterized by small-scale family DPU with a homogenous socio-economic background and similar production practices. Complex linkages between social-ecological components, namely the dairy producers, their herd, their family, consumers of dairy products and the ecosystem, in urban areas differ from peri-urban and rural ones.

In order to quantify resource use efficiency, i.e. feed conversion efficiency, of Bengaluru's DPS, 28 dairy production units (DPU), 7 per DPS, were selected and monitored at 6-week intervals during one year: daily dry matter intake on-farm and at pasture, and energy and nutrient requirements (for maintenance, growth, pregnancy, locomotion, milk production) were collected for each cow. Daily dry matter intake (DMI) per kg of metabolic weight showed distinctly different feeding intensities that were linked to the reliance on self-cultivated forages or pasture or both. Coverage of the requirements of metabolizable energy and crude protein were variable in DPS-1, while in DPS-2, DPS-3 and DPS-4, cows were mostly oversupplied. Milk offtake differed between DPS and, corrected to body weight, was affected by DPS, days-in-milk, DMI, genotype, coverage ratio for metabolizable energy, pregnancy and period of data collection. The extensive DPS-1 had the best feed conversion efficiency (1.00 kg DMI per kg energy-corrected-milk (ECM)), while feed conversion efficiency in DPS-2 (0.71 kg DMI kg^{-1} ECM), DPS-3 (0.77 kg DMI kg^{-1} ECM) and DPS-4 (0.72 kg DMI kg^{-1} ECM) were crippled by the oversupply of cows. The decoupling of crop and livestock production in DPS-1 might however lead to environmental deterioration, especially in the case of urban dairy producers, with limited manure management options.

In order to quantify the global environmental impact of Bengaluru's DPS, i.e. their emission intensity of greenhouse gasses expressed in terms of carbon dioxide equivalents (CO_2-eq), methane and nitrous oxide emissions due to enteric fermentation and manure management system were computed from the previous dataset for six DPU per DPS. The carbon footprint (CF) of milk differed according to the feeding intensity and strategy of each DPS: CF was highest in DPS-3 (1.95 kg CO_2-eq kg^{-1} ECM) and DPS-4 (1.52 kg CO_2-eq kg^{-1} ECM). In opposition, CF was lowest in the extensive DPS-1 (0.91 kg CO_2-eq kg^{-1} ECM) and intermediate in DPS-2 (1.21 kg CO_2-eq kg^{-1} ECM). Cradle-to-farm-gate emission intensity of

Bengaluru’s dairy sector was estimated to be within the range of DPS with similar production levels in other countries.

Overall, the present study highlighted that: i) a range of DPS coexists within Bengaluru’s rural-urban interface, leading to different levels of production intensity, resource use efficiency and global envrionmental impacts; ii) small-scale DPU can be efficient and emission conservative, as they take advantage of local opportunities while dealing with the local constaints of an urbanizing envrionement; iii) urbanization impacts on dairy production are complex: urbanisation lead to changes in labour availability but not directly in (decreasing) land availability for dairy production; it enhanced market integration of rural and peri-urban dairy producers but not structural change in Bengaluru’s dairy sector; at last, it enhanced increasingly more complex linkages between social-ecological components.

By improving understanding of agricultural transitions in the case of dairy production in an urbanizing environment, the present study can support the implementation of future dairy development programs by pointing to local constraints and opportunities and the importance of several social-ecological components that should be considered in such initiatives. The present study further paves the way for research on the impacts of urbanization on milk and livestock production systems in developing and transition countries with a broad system approach.

Zusammenfassung

Im Zuge der Urbanisierung werden Gebiete typischerweise in landwirtschaftlich produktionsorientierte ländliche Gebiete *versus* konsumorientierte städtische Gebiete unterteilt, zwischen denen der Fluss landwirtschaftlicher Güter und Dienstleistungen eine der Hauptverbindungen darstellt. Landwirte und Konsumenten sind Teil eines gemeinsamen sozial-ökologischen Systems, das immer komplexer, gleichzeitig aber auch lockerer wird. Die Rolle der Landwirte als verbindendes Subjekt zwischen Gesellschaft und Umwelt gewinnt dabei an Bedeutung. Indien ist derzeit eines der Länder mit der schnellsten Urbanisierungsrate weltweit, und sein Milchsektor ist der weltweit größte – er stellt die Lebensgrundlage von 70 Millionen Haushalten dar. Indien hat jahrzehntelang zahlreiche Programme zur Entwicklung der Milchwirtschaft unterhalten und die Verbindung zwischen städtischen und ländlichen Gebieten durch den Fluss von Milch(produkten) gefördert. Bisher fehlen allerdings Untersuchungen zu den Auswirkungen der fortschreitenden Urbanisierung auf den Strukturwandel im Milchsektors, Veränderungen in Ressourcenverfügbarkeit und -nutzung durch die Milcherzeuger sowie auf die zunehmende Komplexität der sozial-ökologischen Systeme in deren Zentrum die Milcherzeuger stehen.

Daher ist das Ziel der vorliegenden Dissertation, einen vertieften Einblick in die Auswirkungen der Urbanisierung auf die Milchproduktion zu tätigen; dabei dient der Milchsektor der indischen Megacity Bengaluru (10 Millionen Einwohner) als Fallstudie. Seit den 1970er Jahren ist Bengaluru eine der am schnellsten wachsenden Städte Indiens und profitiert von einem eigenen Entwicklungsprogramm für die Milchwirtschaft. Milchproduktion ist in den (peri-)urbanen Siedlungsgebieten weit verbreitet. Zunächst identifiziert und charakterisiert die vorliegende Arbeit die Milchproduktionssysteme (DPS) die in Bengaluru an der Schnittstelle Stadt-Land koexistieren und zeigt bestehende und potentielle Verbindungen zwischen den sozial-ökologischen Komponenten des Systems „Milch“ auf. Darauf aufbauend werden die Auswirkungen unterschiedlicher Milchproduktionsstrategien auf die Ressourcennutzungseffizienz quantifiziert, d.h. auf die Futterverwertungseffizienz und die globalen Umweltwirkungen in Form von Treibhausgasemissionen. Dabei wird jeweils die räumliche Verteilung der DPS entlang der Schnittstelle Stadt-Land berücksichtigt.

Zur Identifizierung und Charakterisierung von DPS die entlang der Schnittstelle Stadt-Land von Bengaluru koexistieren wurden 337 Milcherzeuger detailliert zu ihrem Produktionssystem befragt, dabei wurde räumlich zwischen sechs Urbanisierungsgraden unterschieden. Anhand einer zweistufigen Clusteranalyse wurden vier DPS ermittelt, die sich in den folgenden fünf Variablen unterschieden: der Urbanisierungsgrad ihres Viertels, die

Eigenerzeugung von Futtermitteln, die Nutzung von (öffentlichen) Weiden, die Zu- und Abgänge von Milchvieh innerhalb der Herde und der Anteil an milchbetonten Genotypen. Das extensive System DPS-1 war entlang der gesamten in Stadt-Land Schnittstelle von Bengaluru vertreten; hier wurden keine eigenen Futtermittel erzeugt sondern öffentliche Flächen als Weiden und zum Ernten von Grünfutter genutzt; außerdem wurden Marktabfällen als Futtermittel eingesetzt. Das halbintensive DPS-2 war in den ländlichen Regionen verankert; seine Fütterungsstrategie beinhaltete den Anbau von Futtermitteln und Weidegang, die Zuchtstrategie war auf milchbetonten Genotypen fokussiert. DPS-3 ähnelte DPS-2 hinsichtlich Verortung und Fütterungsstrategie, war aber nicht auf die Haltung milchbetonten Genotypen spezialisiert. Das intensive DPS-4 war ausschließlich in den ruralen Randbereichen der Stadt angesiedelt, die Fütterungsstrategie beruhte auf dem eigenen Anbau von Futtermitteln aber nicht auf Weidegang. Milcherzeuger aus DSP-1 waren meist landlos und nutzten informelle Vermarktungskanäle, um ihre Milch zu verkaufen. Milcherzeuger aus DPS-2, DPS-3 und DPS-4 verließen sich auf Molkereigenossenschaften für den Bezug von Inputs und zur Vermarktung ihrer Milch. Insgesamt verfügt der Milchsektor von Bengaluru über ein gut etabliertes Netzwerk von Molkereigenossenschaften und wird von kleinen Familienbetrieben mit homogenem sozioökonomischem Hintergrund und ähnlichen Produktionspraktiken charakterisiert. Die komplexen Verbindungen zwischen den sozial-ökologischen Komponenten des Systems „Milch“, nämlich den Milcherzeugern, ihren Herden, ihren Familien, den Verbrauchern und dem Ökosystem sind in den urbanen Gebieten anders ausgeprägt als in den peri-urbanen und ländlichen Gebieten.

Um die Ressourcennutzungseffizienz und speziell die Futterverwertungseffizienz zu quantifizieren wurden 28 Milchviehbetriebe ausgewählt (7 pro DPS). In Intervallen von sechs Wochen wurden während eines Jahres die tägliche Trockenmasseaufnahme (TMA) aller Kühe im Stall und auf der Weide sowie ihr Energie- und Proteinbedarf (für Erhaltung, Wachstum, Trächtigkeit, Fortbewegung, Milchproduktion) erfasst. Der Verzehr von Trockenmasse (TM) pro kg metabolischer Körpermasse zeigte deutliche Unterschiede in der Fütterungsintensität, die mit dem eigenen Anbau von Futtermitteln, der Weidenutzung oder beiden Faktoren zusammenhingen. Die Energie- und Rohproteinversorgung der Kühe variierte stark in DPS-1, in DPS-2, DPS-3 und DPS-4 wurden die Kühe meistens überversorgt. Die Milchleistung (korrigiert um den Einfluss des Körpergewichts) in den vier DPS war deutlich unterschiedlich und wurde beeinflusst durch DPS (Management), Genotyp, Laktationstag, Trächtigkeit, TMA, Energieversorgung und Zeitpunkt (Saison) der Datenerfassung. Im extensiven DPS-1 wurde die beste Futterverwertungseffizienz ermittelt (1,00 kg TM pro kg energiekorrigierte Milch (EKM)), während die Futterverwertungseffizienz in DPS-2 (0,71 kg TM kg^{-1} EKM), DPS-3 (0,77 kg TM kg^{-1} EKM) und DPS-4 (0,72 kg TM kg^{-1} EKM) durch das Futterüberangebot herabgesetzt wurde. Die fehlende Kopplung von Ackerbau und Tierhaltung in DPS-1 kann jedoch zu Umweltverschmutzung beitragen, insbesondere bei urbanen Milcherzeugern mit begrenzten Möglichkeiten für das Dungmanagement.

Um die Umweltwirkungen von Bengalurus DPS zu quantifizieren wurde die Emissionsintensität von Treibhausgasen in Form von Kohlendioxid-Äquivalent (CO_2-äq) berechnet. Dazu wurden aus dem Fütterungsdatensatz der sechs Milchviehbetriebe pro DPS die Methan- und Distickstoffoxid-Emissionen aufgrund von enterischer Fermentation und Dungmanagement berechnet. Die CO_2-Bilanz der Milcherzeugung unterschied sich je nach Fütterungsintensität und Managementstrategie der DPS, wobei die höchsten Werte für DPS-3 (1,95 kg CO_2-äq kg^{-1} EKM) und DPS-4 (1,52 kg CO_2-äq kg^{-1} EKM) berechnet wurden. Im Vergleich dazu war die Bilanz des extensiven DPS-1 (0,91 kg CO_2-äq kg^{-1} EKM) am niedrigsten und die des DPS-2 (1,21 kg CO_2-äq kg^{-1} EKM) intermediär. Die aus diesen Daten geschätzte „cradle-to-farm-gate“ Emissionsintensität des Milchsektors von Bengaluru war damit vergleichbar mit dem von Systemen ähnlicher Produktionsniveaus in anderen Ländern.

Insgesamt zeigt die vorliegende Studie, dass i) entlang Bengalurus ländlich-städtischer Schnittstelle eine Reihe von DPS koexistieren, die durch unterschiedliche Niveaus der Ressourcennutzungseffizienz und der globalen Umweltwirkungen charakterisiert sind; ii) kleinskalige DPU nicht systematisch ineffizient oder emissionsintensiv sind, da sie oft lokale Ressourcen nutzen und gleichzeitig mit lokalen Einschränkungen zurechtkommen; iii) die Verstädterung komplexe Auswirkungen hat: Veränderungen in der Verfügbarkeit von Arbeitskräften, aber nicht direkt in (abnehmende) Verfügbarkeit von Land; verbesserte Marktintegration von ländlichen and periurbanen Milcherzeugern aber kein Strukturwandel des Milchsektors; zunehmend komplexere Verbindungen zwischen sozial-ökologischen Komponenten. Durch ein vertieftes Verständnisses landwirtschaftlicher Transformationsprozesse, in diesem Fall der Milchproduktion in einem sich schnell urbanisierenden Umfeld, kann die vorliegende Studie die Umsetzung zukünftiger Milchentwicklungsprogramme unterstützen, indem sie auf lokale Einschränkungen und Möglichkeiten sowie auf die Bedeutung mehrerer sozial-ökologischer Komponenten hinweist, die alle bei solchen Initiativen berücksichtigt werden sollten. Die vorliegende Studie eröffnet ausserdem neue Perspektiven für weitergehende systemische Forschung zu Fragen der Auswirkungen von Urbanisierung auf Milchviehhaltung und andere Tierhaltungssysteme in den sogenannten Entwicklungs- und Schwellenländern.

General Introduction

1.1 A framework to livestock production in an urbanizing environment

1.1.1 A system approach

A system approach starts with the identification and characterization of the system, as knowledge is key to its improvement, repair, duplication or comparison (Ikerd, 1993; Spedding, 1988). Spedding (1988; p. 18) defines a system as "*a group of interacting components, operating together for a common purpose, capable of reacting as a whole to external stimuli: it is unaffected directly by its own outputs and has a specified boundary based on the inclusion of all significant feedbacks*". Broadly speaking, livestock production systems are thus systems, whose outputs are goods and services specifically provided by the rearing of livestock, usually food provision (milk, meat, eggs), and are limited to farm-level components. Their further characterization is however context-specific. Statistical classification methods (see Dossa et al. (2011) for a review) are thus often used to highlight naturally occurring clusters of data, which can be interpreted as specific livestock production systems. In the context of an urbanizing environment, (peri)-urban livestock production systems have been characterized through two-step cluster analysis (Dossa et al., 2011; Roessler et al., 2016), which allows the simultaneous consideration of continuous and categorical context-specific variables for clustering. A two-step cluster analysis thus potentially reflects the complexity and specificities of local livestock production systems more accurately than a cluster analysis considering only one type of context-specific variables. Yet, this accuracy depends on the range of collected data, which is defined by expert knowledge and previous studies, their focus and their quality.

1.1.2 Urbanization and rural-urban linkages

Urbanization stands for the settlement of a large human population at high density (Millennium Ecosystem Assessment, 2005) and by extension, the rise of (mega)cities and associated physical transformation such as the conversion of agricultural lands into industrial or residential areas. Urban areas resulting from urbanization and rural areas are generally dichotomized, spatially and on a sector basis: urban areas are consumption oriented areas with no agricultural production by opposition to rural areas, which are production oriented with low consumption level (Lerner and Eakin, 2011; Tacoli and Vorley, 2015). The flow of agricultural goods and services from rural to urban areas is called a rural-urban linkage and often overlooks other rural-urban linkages such as the flows of persons, financial capital, information or even waste (Tacoli, 2003; Termeer et al., 2019). Shifts from a rural to an urban spatial distribution of population is a major trend of the 21st century and a demographic driver of change for rural-urban linkages. Yet, the spatial and sectorial dichotomization of rural and urban areas is fairly recent.

A (historical) perspective on urbanization and rural-urban linkages. The Neolithic revolution started roughly 10’000 years ago in the Fertile Crescent (Middle East) and was both a demographic revolution and the beginning of agriculture: by adopting food-production practices and domesticating plants and later animals, humans in the Fertile Crescent and in later agricultural homelands shifted from being hunter-gatherers to sedentary farmers (Curry, 2013; Diamond and Bellwood, 2003; Steel, 2008). The adoption of new technologies and sedentary lifestyle resulted in the first human settlements and, over millennia, lead to the development of larger and more complex societies, and the emergence of human civilizations (Steel, 2008). A prominent example of the coevolution of human populations and agriculture is the emergence of a genetic mutation causing the persistence of lactase in adulthood 7’500 years ago in central Europe (Curry, 2013). The ability to digest the lactose naturally present in raw milk improved the nutritional status of the European populations, which fostered population growth and the expansion of dairying (Curry, 2013). At the historic starting point of human societies and agriculture, the spatial and sectorial dichotomization of urban and rural areas was thus at most marginal and rural-urban linkages inexistent.

Fast-forward to contemporary times, the spatial and sectorial dichotomization of urban and rural areas is increasingly stronger and rural-urban linkages increasingly more complex. Although the sustenance of a large city through cereal imports can be traced back to Ancient Rome, the perishable nature of animal products such as milk required the maintenance of livestock in (peri-)urban areas for many additional centuries (Steel, 2008) e.g. in 1829, there were 71 cowsheds within London (Atkins, 1977). The moving of livestock out of cities after the Industrial Revolution was the decisive step in the western spatial and sectorial dichotomization of rural and urban and the emergence of agricultural flows as a rural-urban linkage (Lerner and Eakin, 2011; Steel, 2008; Tacoli and Vorley, 2015). This spatial and sectorial shift was again a result of technological advances in transport and food preservation, from which contemporary western food regimes emerged (Butler, 2012; Lamine, 2015; Steel, 2008). Yet, contemporary western food regimes foster additional rural-urban linkages, e.g., financial links in the forms of monetary subsidies, or informative links in the form of production or animal-welfare labels, and a growing importance of institutions shaping them (Lamine, 2015; Termeer et al., 2019). The historical case of livestock intensification in the Netherlands from 1870 to 2017 descried by Termeer et al. (2019) is an excellent yet rare case study on the nature of rural-urban linkages and, in the background, of historical agricultural transitions in an urbanizing environment. Historical cases of urban milk supply in London from *circa* 1790 to 1914 by Atkins (1977) and in Singapore in the 20th century by Wikkramatileke and Singh (1969) are also worth mentioning.

In Western countries, growth rates of urban agglomerations already slowed down and the bulk of urbanization until 2030 is expected to happen in West Africa and Asia (United Nations, 2018a). Interestingly, research in urbanizing tropical countries on on-going transformation of their agricultural sector and rural-urban linkages challenges the spatial and sectorial dichotomization of urban and rural areas. Firstly, this is due to the context-dependent definition of urbanization, e.g. when definition of an urban settlement depends on its population size and spatial shape, which are relative to national context (Tacoli, 1998). This prompted the use of the growth rate of urban areas rather than their absolute size by the United Nations (2018a) to quantify urbanization. Yet, the definition of urban areas can also take into account geographical features such as percentage of built-up areas (Hoffmann et al., 2017) or specific infrastructures (Philippine National Statistics Office, 1992; Tingbé-Azalou, 1997), while some definitions include a sectorial criteria (Philippine National Statistics Office, 1992) and others don't (Hoffmann et al., 2017; Tingbé-Azalou, 1997). Distinction between urbanization and correlated characteristics should be however maintained; e.g., increased demand for agricultural products and shift in diet preferences is often attributed to urbanization, yet growing income seems to be the underlying reason, which blurs the spatial restriction of a growing demand to urban areas only (Tacoli and Vorley, 2015). Finally, spatial rural and urban dichotomization often rests on a monocentric and gradual approach to urbanization, overlooking the provision of goods and services to rural populations by urban areas of different size and accessibility (Tacoli, 2003). The sectorial dichotomization of rural and urban areas is first challenged because of, on one hand, the existence of rural consumers, which does not fit the definition of rural areas as solely production-oriented (Tacoli and Vorley, 2015). On the other hand, urban areas are considered consumption oriented, which does not account for the existence of (peri-)urban agricultural production systems. On top of these considerations, complex rural-urban linkages across space and sector exist in the form of, e.g., urban dwellers owning rural properties and sending remittances to rural areas, income-generating off-farm activities of rural inhabitants in the cities, or rural dwellers' daily or seasonally commuting to a city (Krüger, 1998; Tacoli, 2003). Finally, the spatial and sectorial dichotomy between rural and urban areas is challenged by the existence of peri-urban areas, not so much as a transition space from rural to urban but a mix of both, where sectorial interaction and linkages as flows of material, people and wastes are the most intensive (Lerner and Eakin, 2011; Tacoli, 2003, 1998).

1.1.3 Social-ecological system and resilience

A (livestock) production system is mostly limited to the boundaries of the production unit but the definition of a system by Spedding (1988) can be applied at a larger scale to include social-ecological components outside the boundaries of the production unit "*capable of reacting as a whole*" and "*all significant feedbacks*". Social-ecological systems (SES), which provide agricultural goods and services, are thus made of a network of different socioeconomic actors - producers and their families, the consumers, intermediaries of the value chains and institutions involved in the regulation of the value chain – and of ecological components, such as the ecosystem, resource units and biological processes (Ostrom, 2007; Termeer et al., 2019). Because they typically provide agricultural goods and services, they exist across rural and urban areas with the flows of agricultural products across the rural-urban interface constituting the predominant link between its central components: producers and consumers. SES components are further connected by different flows of material, people, information or financial capital: on one hand, through consumption patterns society influences goods and services produced by farmers and their management practices (Figure 1.1; Sundkvist et al., 2005). SES thus shape how farmers use critical agricultural resources (land, water, capital and labour) and hence determine agricultural production systems. On the other hand, environmental externalities of the thus-shaped production systems act as a feedback to society (Sundkvist et al., 2005).

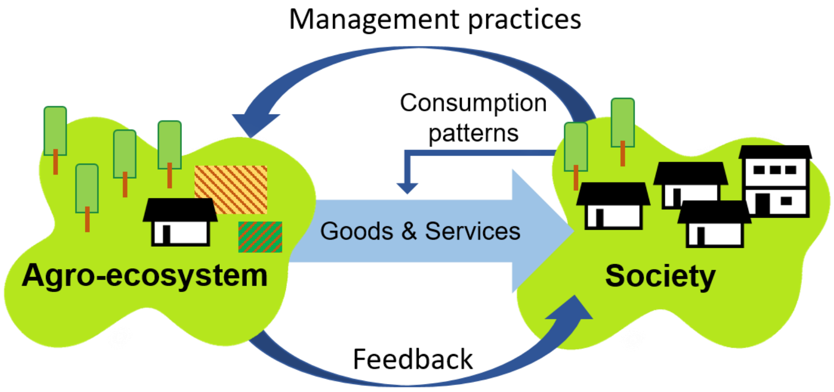

Figure 1.1 Illustration of an social-ecological system and the different feedback mechanisms between its components (adapted from Sundkvist et al., 2005).

The SES framework had been designed to improve the identification and understanding of an outcome as results of complex interactions between social-ecological components, such as unsustainable resource use (Ostrom, 2007). Cumming et al. (2014) characterized SES preserving the local equilibrium between resources use and consumption as “green-loop” and theorized that such equilibrium is maintained through tight feedbacks between the SES components. By opposition, “red-loop” characterizes SES shifting toward an unsustainable equilibrium as consumption outgrows local resources, which leads to over-exploitation of local resources, expansion of the urban foodshed and outsourcing of negative environmental externalities (Cumming et al., 2014; Kelly-Reif and Wing, 2016; MacDonald et al., 2015).

A SES shifts from a “green-loop” to “red-loop” when the linkages between its components loosen and the feedbacks between them weaken (Cumming et al., 2014; Sundkvist et al., 2005; Termeer et al., 2019). Termeer et al. (2019) underline the importance of human agency, namely the capacity of people to act voluntary and independently, as component of efficient feedback mechanisms. When SES components are tightly linked, socioeconomic actors of a SES feel concerned by the environmental issues generated by their consumption and can decide to act on it, e.g. by changing their consumption patterns and volumes or by calling for stricter environmental regulations. The role of institutions is however increasingly crucial e.g. in the success of dairy cooperatives (Bijman, 2018) but especially to compensate for unavoidable weakening of feedbacks (Termeer et al., 2019). Tight linkages between SES components also provide resilience to SES; the latter is divided by Termeer et al. (2019; p. 2) in three sub-capacities:

- **Robustness**: “the capacity to maintain the same functions and desired levels of outputs despite the occurrence of perturbations”
- **Adaptability**: “the capacity to respond to shocks and stresses by adjusting internal processes”
- **Transformability**: “the capacity to create a fundamentally new system to capture novel opportunities or respond to either severe anticipated/unanticipated shocks or enduring stress that make the earlier system untenable”

1.2 Livestock production systems in an urbanizing environment

1.2.1 Agricultural transition

Farming systems are characterized by their use of essential agricultural resources, such as land and labour. Urbanization is a driver of change in farming systems as it induces a transition in the use of essential agricultural resources, either because of a shift in the supply side or in the demand side or both. At farm-level, the agricultural transition due to urbanization results in distinct development trends of intensification versus extensification, or diversification versus specialization.

Shift in the supply side. The most direct impact of urbanization is its physical fallout, namely the decreased availability of agricultural land in and around urban areas as arable land and pastures are converted into residential or industrial areas, and the agricultural landscape gets fragmented (Satterthwaite et al., 2010). Urbanization also affects labour availability since urban areas increase opportunity costs of family labour, especially of a younger best-educated generation. Off-farm occupation of family labour can however create new job opportunities for hired labour, which can benefit those whose access to resources is too compromised to pursue an agricultural economic activity on their own (Satterthwaite et al., 2010; Tacoli, 2003).

Shift in the demand side. Countries in the Global South see a massive increase in consumer demand for animal products as they urbanize, which is termed “livestock revolution” (Seré et al., 2008). Urbanization indirectly contributes to this increased demand as not only the number of people involved in agriculture decrease (Satterthwaite et al., 2010) but the (new) urban dwellers benefit of income increases which in turn foster a shift in consumption patterns (Erler and Dittrich, 2017; Regmi and Dyck, 2001).

Intensification versus extensification. Because urbanization reduces land and labour availability, farmers are implicitly pushed to produce as much goods as possible with less inputs. As urbanization, rather than proximity to an urban area in itself, increases market quality by easing access to production inputs, farmers are foremost given the opportunity to improve their production through the intensified use of inputs such as concentrate feed or modern animal and plant genetics (Duncan et al., 2013). Thus, the access to essential agricultural resources is a determinant for the trend towards intensification of production systems in an urbanizing environment (Zoomers and Kleinpenning, 1996). Although trends of intensification and extensification can coexists within the same urbanized space, as documented by Roessler et al. (2016), and subsistence often motivates extensive (peri-)urban production (Graefe et al., 2019), drivers of extensification in commercial-oriented production in an urbanizing environment are not reviewed in-depth.

Diversification versus specialization. The incentive for family labour to pursue off-farm economic activities drives occupational diversification (Bah et al., 2003). However, the drive to intensify production also favours specialization of production by focusing on only one product as efficiently as possible rather than providing a whole bundle of goods and services.

1.2.2 Market integration

At sector-level, urbanization results in the development of the agricultural sector from a subsistence-oriented production to a commercial agricultural sector; that is the integration of farmers into formal value chains. Development of dairy production through market integration is typically seen as an efficient way of improving livelihoods in rural areas as it is not necessarily land intensive (Janssen and Swinnen, 2019; Wouters and van der Lee, 2010).

The role of dairy cooperatives. Dairy cooperatives are a bottom-up participative approach to organize the supply side of milk and ease access to production inputs and marketing channels (Wouters and van der Lee, 2010). Although a bottom-up approach, institutional support is a key component of dairy cooperatives' success on the long run (Bijman, 2018). Typically, dairy cooperatives will focus on improving milk production through easier access to concentrates feeds, genetically improved animals through artificial insemination and extension services (Chagwiza et al., 2016; Wouters and van der Lee, 2010). Dairy cooperatives also drive standardization and improvement of milk quality, which are necessary prerequisites for dairy producers to enter into a formal value chain (Ikerd, 1993; Tacoli and Vorley, 2015).

Market integration and resilience. Market integration of farmers challenges the resilience of SES providing goods and services through the rearing of livestock due to four processes that decrease the quality of linkages between producers and consumers: distancing, homogenization, intensification and specialization (Sundkvist et al., 2005; Termeer et al., 2019). According to Termeer et al. (2019), intensification leads to decoupling resources uses from local ecosystems, while specialization decouples crop and livestock production. Because of the dichotomization of rural and urban spaces, agricultural goods travel longer distances and homogenization of production processes and products results in the loss of local knowledge necessary to maintain a sustainable use of local resources.

1.2.3 (Peri-)urban livestock production systems

As a rural activity taking place in urban areas, (peri-)urban agricultural production presents a sectorial interaction that challenges the dichotomization of rural and urban areas (Tacoli, 1998). (Peri-)urban dairy production it is fairly common in the Global South and has been documented in Cairo, where adaptation strategies to urbanization were highlighted (Daburon et al., 2017), in Ethiopia where it accommodates for religious specificities impacting the local dairy sector (D'Haene et al., 2019; D'Haene and D'Haese, 2019), in Burkina Faso where it lacks resources use efficiency (Schlecht et al., 2019), and in Mali (Amadou et al., 2015), Burkina Faso and Ghana where specialisation and intensification trends are found (Roessler et al., 2016).

Opportunities for (peri-)urban livestock production systems. (Peri-)urban livestock production systems usually directly improve the livelihood of (peri-)urban producers by providing food to the household (Graefe et al., 2019). (Peri-)urban producers are typically also motivated by market opportunities and the viability of their activity depends of the identification of a demand for their products (Graefe et al., 2019; Lapar et al., 2010). (Peri-)urban livestock production systems can also be motivated by the preservation of the cultural identity of the households (Lerner and Eakin, 2011; Tacoli, 1998). Furthermore, inequalities in cities are often huge (Anand and Thampi, 2016) and (peri-)urban livestock production systems are often informal and direct, supplying agricultural goods at low prices for marginal urban inhabitants. By suppling highly perishable animal products, they also compensate for poor transport and cooling infrastructures in the Global South (Lamine, 2015; Prasad et al., 2019; Steel, 2008). Consumer preference for fresh products, trust in the direct relationship with a producer as a guarantee of quality and local knowledge such as boiling raw milk before consumption reinforce the market opportunities of (peri-)urban producers (Lapar et al., 2010). (Peri-)urban areas also offer specific opportunities for producers such as novel inputs – e.g., organic urban wastes to be used as livestock feeds – and direct marketing channels, which can be financially more rewarding than in rural areas (Hemme and Otte, 2010).

Constraints for (peri-)urban livestock production systems. Constraints of (peri-)urban agriculture are linked to the integration of livestock within the city (Steel, 2008), the sanitary risks of the close proximity between humans and animals (Butler, 2012) but also to the consumption of animal products from informal value chains (Tacoli and Vorley, 2015), waste management (Butler, 2012), and the decoupling of crop and livestock production, which wastes nutrients and transforms cities into "nutrient sink" (Drechsel and Kunze, 2001; Prasad et al., 2019).

1.3 Dairy production in an urbanizing environment: the case study of Bengaluru, India

1.3.1 The national context

Urbanization. One person out of six on the planet currently lives in India. With more than one billion inhabitants, it is the second most populous country in the world (World Bank, 2018a). India classifies its administrative units as urban when they have an administrative status as town (e.g., municipal corporation) or fulfil three criteria: a minimum population of 5'000 people, less than 25% of the male population employed in the primary sector and a high population density (minimum 400 people per km^2; Government of India, 2011). In 2018, 34% of all Indian citizens lived in urban areas (World Bank, 2018b).

Dairy sector. The demographic scale of India is matched by the scale of its dairy sector: India is the second largest producer of cattle milk worldwide (year 2018; FAOSTAT, 2019) but all dairy animals confounded, it is the largest dairy producer worldwide since 1996. In 2019, India produced twice as much milk as the USA, who is the second dairy producer worldwide (FAOSTAT, 2019). This massive production is largely due to India having the largest buffalo herd and the second largest herd of cattle worldwide (FAOSTAT, 2019). Milk and dairy products account for around two thirds of the Indian livestock sector's value (Mayberry et al., 2017; Ministry of Agriculture, 2014). Milk also has a high nutritional value as a major source of animal protein in a country where 40% of the population is vegetarian (Government of India, 2014). Yet, milk consumption per capita is low (145 g per capita and day versus 227 g in Europe, year 2003; FAOSTAT, 2019).

Today's dairy sector in India is built on the success of Operation Flood: launched in the 1970s, Operation Flood was a large-scale and decades-long pro-poor dairy development program, which successfully tackled the underdevelopment of dairy production in rural areas. This was achieved by improving infrastructures, since dairy cooperatives scaled-up milk extension services, processing and marketing, enabled rural production to reach urban consumers, and reinforced rural-urban linkages (Cunningham, 2009). Between 1970 and 1996 and across 170 milksheds[1] in 362 districts, Operation Flood tripled the productivity per dairy animal, raised the number of dairy cooperatives from 1'600 to 70'000,

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[1] Delimited geographical area supplying milk for a given city.

doubled the income of landless farmers and ended the decades-long dependency of India on milk imports (Cunningham, 2009).

Despite all infrastructural improvements introduced by Operation Flood, smallholders with two to five cows still produce 80% of the national milk volume today (Cunningham, 2009) and the productivity per dairy cattle is low. This low productivity is often explained by poor feeding (poor diet quality, extensive pasture use, low use of concentrated feeds, feed scarcity and seasonal variability; Mayberry et al., 2017), poor genetics (low productivity of local dairy cattle; Ministry of Agriculture, 2014) and poor milking practices (short lactations, long calving intervals; Duncan et al., 2013). Heat stress due to the tropical weather of India can also partly explain low productivity of *Bos taurus* dairy cattle with otherwise high genetic production potential (West, 2003).

The cow in the Indian society. The well-known sacred status of cows in India is a thousand years old religious and national legacy, which lead to cow slaughter being legally banned in almost all of today's India. Old and unproductive dairy cows are often kept in cattle shelters known locally as *gaushala*, which host about one seventh of the total Indian cattle population. This practice also fuels the "sacred-cow controversy" in scientific literature on externalities of such a large population of "useless" cattle (Kennedy et al., 2018). Cows provide socio-cultural services to Indian society as their existence is enjoyed (Figure 1.2) and they are still part of many religious ceremonies, e.g. blessing of a new house (Narayan, 2018; Vohra, 2012). An longstanding symbol of wealth and prosperity, cows are central to the livelihoods of 70 million Indian households, providing them with milk and dairy products, draught power, dung, urine and income (Cunningham, 2009), and preserving their cultural identity (Crane, 2010; Lerner and Eakin, 2011).

Figure 1.2 A boy, while waiting to enter a temple, idly pets a cow, which freely moves in the crowd.

1.3.2 The city of Bengaluru

Capital of the southern Indian state of Karnataka, Bengaluru, formerly Bangalore, is located on the Deccan plateau at 920 meters above sea level. Its climate is hot semi-arid (average maximum temperature 29.5°C, average minimum temperature 18.5°C, 948 mm of annual rainfall; monthly average 2013-2017, weather station data of the University of Agricultural Sciences Bangalore, GKVK campus). The dry season (March-May) is followed by a monsoon season (June-October) and winter (November-February).

Formerly nicknamed “Garden City” because of its numerous trees, reputed for its mild climate and numerous lakes, Bengaluru metropolitan area was estimated to be built-up only at 23% to 24% in 2007 (Figure 1.3; Sudhira et al., 2007). Built-up areas in the Bangalore Urban district however increased by 1’039% in 50 years (1965 to 2018; Brinkmann et al., 2020). Since the 1970s, Bengaluru was one of the fastest growing cities in India, driven by an (IT) industrial boom, which earned her the new nickname “Silicon Valley of India” (Sudhira et al., 2007; Verma et al., 2017; World Bank, 2013). Its population growth was fuelled mostly by migrants attracted by new economic opportunities (Sudhira et al., 2007) and led to more than 10 million citizens at present (Kumar et al., 2016). Being one of the largest urban agglomerations in India today and a large metropolitan economy even by world standards (Parilla et al., 2015), unplanned growth especially in peri-urban areas results in loss of agricultural land, lakes and green spaces (Verma et al., 2017). Despite urbanization, (peri-)urban agriculture in Bengaluru is not uncommon, motivated by the (original) population’s quest for additional food and income sources (World Bank, 2013). Most (peri-)urban farmers cultivate crops but dairy production within the city also exists (Prasad et al., 2019; World Bank, 2013).

1.3.3 The dairy sector of Bengaluru

Based on the model of Operation Flood, a Karnataka Dairy Development Project was launched in 1974 and the resulting networks of dairy cooperatives and producers is now known as the Karnataka Milk Federation (KMF), the second largest milk cooperative in India (Alderman, 1987; Karnataka Milk Federation). Ten years after the launch of the Karnataka Dairy Development Project differences between cooperatives’ members in Karnataka and non-cooperative members were already reported by Alderman (1987): at the time, the average herd size of cooperative members was 5.5 animals (approx. one quarter of male animals; milk herd composed of 36% local cattle, 17% crossbreed cows and 47% buffaloes) versus a herd

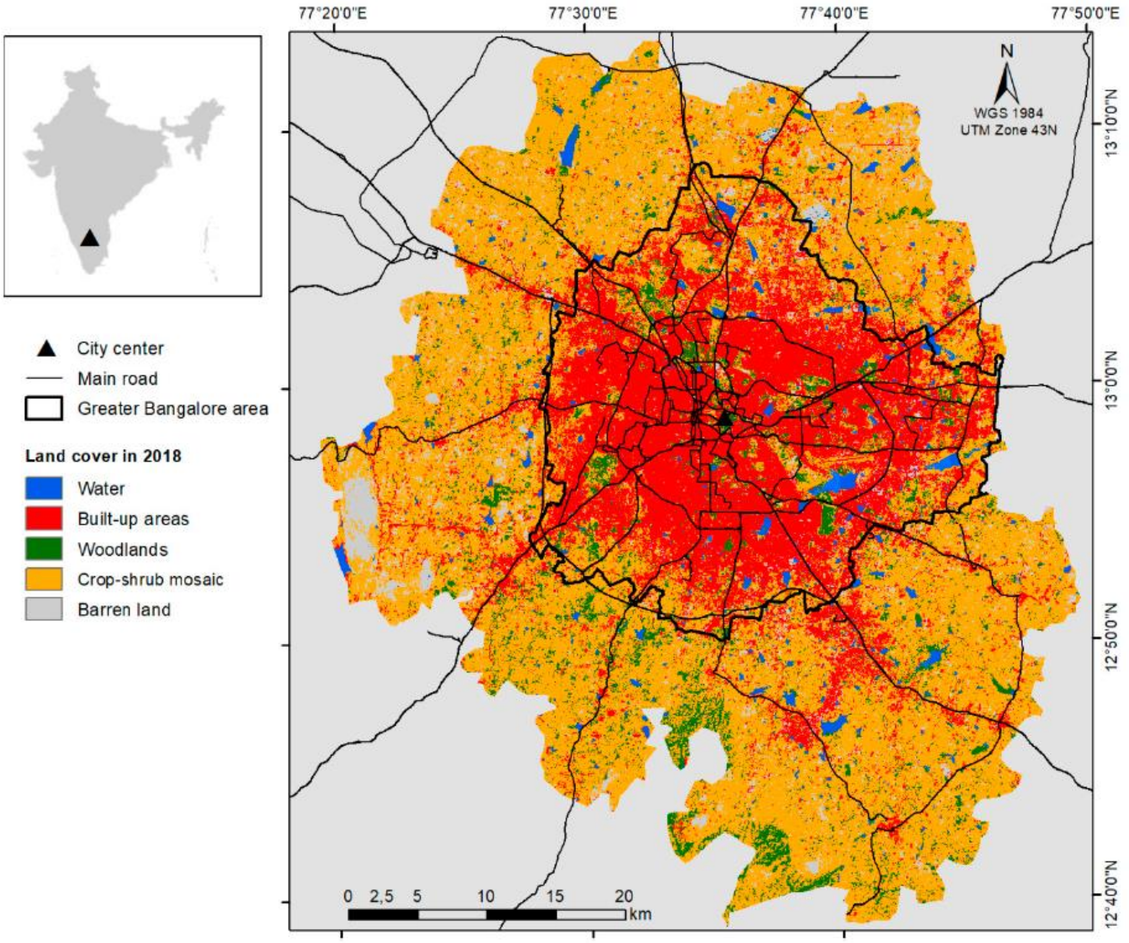

Figure 1.3 Location of Bengaluru within India, land cover types in Bangalore Urban district and the Great Bangalore area delimited in black (Brinkmann et al., 2020).

size of non-cooperative members of 4.7 animals (approx. one quarter of male animals; milk herd composed of 51% local cattle, 5 % crossbreed cows and 44% buffaloes). The rearing of multi-generation crossbreeds was however difficult at that time, but the membership in a cooperative clearly increased the share of commercialized milk per household.

Today, the administrative district of Bengaluru Urban has a bovine population of 145’000, of which 132’000 are female: 83% are crossbreeds, 11% local cattle and 6% buffaloes (National Dairy Development Board, 2015). Karnataka hosts six local cattle breeds, of which five are used for draught purposes (Hallikar, Amritmahal, Khilari, Kirshna Valley and Malnad Gidda) and one for dual purpose (Deoni); to this adds one local buffalo breed used for milk production (Pandharpurri; National Dairy Development Board, 2015). In the district of Bangalore Urban, a crossbreed cow yields on average 5.9 kg of milk per day, a local cow 2.4 kg of milk per day and a female buffalo 2.5 kg of milk per day (National Dairy Development Board, 2015). In Bangalore Urban, 649 dairy cooperatives are registered with the Karnataka

Milk Federation, which operates several milk processing plants, cattle feed plants and a breeding centre in and around Bengaluru (Karnataka Milk Federation). Dairy cattle are a common sight in Bengaluru (Figure 1.4) and (informal) (peri-)urban dairy production contribute to meet Bengaluru's demand for milk (Prasad et al., 2019).

Figure 1.4 Business as usual: close to Bengaluru's city centre, two cows resting on a sidewalk

1.3.4 Study outline and research objectives

The present study aims to provide deeper insights into the impacts of urbanization on dairy production by taking dairy production in the rural-urban interface of Bengaluru as case study. The present study particularly focusses on providing insights on structural change in Bengaluru's dairy sector, (spatially explicit) shifts in resources availability and use by dairy producers in an urbanizing environment and resulting resource use efficiency, (spatially explicit) environmental impacts of dairy production systems in an urbanizing environment and highlighting the complexity of the social-ecological systems that centres around dairy producers and their components. By collecting non-experimental data in a system approach, the present study aims to provide a detailed documentation on local dairy production systems at all urbanization levels, their characteristics and practices (Figure 1.5) and to highlight potential improvements within the capacities of local social-ecological systems. The present work therefore follows the subsequent research objectives:

- To identify and characterize dairy production systems in Bengaluru's rural-urban interface, including their spatial distribution and intensification level, and to highlight potential linkages between social-ecological components in an urbanizing environment (Chapter 2)

- To quantify resource use efficiency, i.e. feed conversion efficiency, of Bengaluru's dairy production systems to challenge the hypothesis that urbanization leads to intensification and efficient resource use (Chapter 3)
- To quantify global environmental impact, i.e. greenhouse gas emissions due to livestock, of Bengaluru's dairy production systems to assess the impacts of local differences in intensification level due to an urbanizing environment (Chapter 4)

At last, the methodological considerations, results and insights provided in previous chapters are discussed in relation to agricultural transition at farm-level, market integration of dairy producers and the SES framework (Chapter 5).

Figure 1.5 A dairy cattle freely grazing on a public ground within Bengaluru; a common practice of urban dairy production.

Typology of dairy production systems and linkages in the rural-urban interface of Bengaluru

2.1 Introduction

As rural areas are taken over by rapidly expanding cities, the role of farmers as a link between society and environment becomes crucial: the spatial flow of agricultural products between rural producers and their urban consumers is a rural-urban linkage at the heart of complex modern social-ecological systems (SES) extracting local resources (Cumming et al., 2014; Francis et al., 2005; Tacoli, 2003). SES components are further linked by different flows of material, people, information and financial capital: on one hand, through consumption patterns, society influences the goods and services produced by farmers and their management practices (Sundkvist et al., 2005). SES thus shape farmers' use of critical agricultural resources (land, water, capital and labour) and accordingly agricultural production systems. On the other hand, environmental externalities of the thus-shaped agricultural production systems act as a feedback to society (Sundkvist et al., 2005). SES are depicted as "green-loop" when they maintain an equilibrium between local resource use and human population size (Cumming et al., 2014), which is possible when the links between SES components are tight and feedbacks effective (Sundkvist et al., 2005; Termeer et al., 2019). By its nature and scope, urbanization increases disconnects and weakens feedbacks between SES components through the processes of distancing, homogenization, intensification and specialization (Cumming et al., 2014; Francis et al., 2005; Sundkvist et al., 2005; Termeer et al., 2019). Urbanization first nurtures distancing by dichotomizing rural and urban worlds spatially and on a sectoral basis, with the rural space dedicated to agricultural production and the urban one to consumption (Lerner and Eakin, 2011; Tacoli, 2003). Spatial and sectoral dichotomization between SES components leads to further "abstract" distancing: i) psychological; that is the concerns of the consumer regarding social and ecological consequences of their consumption decreases, especially regarding negative environmental externalities (Francis et al., 2005); and ii) structural; that is intermediaries in the value chain are multiplied as an increased spatial distance between production and consumption implies an increased durability of primary agricultural products made possible only by processing, and an increased in transport distances (Butler, 2012; Lamine, 2015; Sundkvist et al., 2005). Secondly, urbanization nurtures homogenization of production systems and products as a follow-up of distancing: homogenization guaranties quality and safety for the disconnected consumers and economic efficiency for the intermediaries (Daburon et al., 2017; Prasad et al., 2019; Sundkvist et al., 2005). Third, urbanization nurtures agricultural intensification through decreased availability of two critical agricultural resources: i) land, because of conversion of agricultural land into built-up areas and the fragmentation of the agricultural landscape; and ii) labour, as people, especially young, move to cities in search of better economic opportunities (Satterthwaite et al., 2010; Tacoli, 2003). Urbanization additionally nurtures agricultural intensification by easing farmers' access to inputs and marketing channels (Duncan et al., 2013). At last, urbanization nurtures agricultural specialization by focusing on a single, main output, rather than on the total bundle of goods and services provided by agroecosystems, and by assigning a monetary value to agricultural products, pushing farmers to increase their economic efficiency (Butler, 2012; Prasad et al., 2019; Sundkvist et al., 2005). Under the pressure of urbanization, disconnects between SES components thus increase and feedbacks weaken, inducing a shift in SES toward unsustainable use of local resources or “red-loop” conditions (Cumming et al., 2014).

Having the second largest population in the world (World Bank, 2018a), India is also a rapidly urbanizing country with presently 34% of its population living in cities (United Nations, 2019; World Bank, 2018b). With 40% of the population being vegetarian (Government of India, 2014), milk is a vital source of animal protein but, despite being the largest milk producer in the world since 1996 (FAOSTAT, 2019), daily milk consumption is low with 145 g per capita (versus 227 g per capita in Europe, avg. year 2003; FAOSTAT, 2019). In the 1970s', the Indian government launched a decades-long development programme called *Operation Flood* that focused on dairy production as a vital rural-urban linkage (Cunningham, 2009). Operation Flood successfully scaled up rural milk production, marketing and processing through dairy cooperatives and improved infrastructures, to supply urban areas (Cunningham, 2009). Today's Indian dairy sector rests on numerous rural but also (peri-)urban smallholders, sometimes involved in informal marketing channels (Cunningham, 2009; Prasad et al., 2019).

The urbanization level of an environment represents distinct sets of opportunities and constraints for a farmer in terms of available resources and linking flows between social-ecological components, shaping a variety of production systems. Distinct livestock production systems coexisting within the same (peri-)urban space have been documented in various major West African cities (Amadou et al., 2012; Dossa et al., 2015; Roessler et al., 2016), ignoring however the livestock production systems at the rural periphery of the cities. Taking dairy production in India as an example for production systems and SES linkages in an urbanizing environment, the present study considers urban, peri-urban and rural areas in and around an emerging megacity to tackle the following research questions: i) do distinct dairy production systems (DPS) coexist along a rural-urban interface (RUI)?; ii) how does the spatial distribution of these DPS relate to urbanization level?; iii) which potential linkages between social-ecological components of these DPS do exist in terms of flows of material, people, information or financial capital along the RUI? To answer these questions, we focused on the emerging megacity of Bengaluru in southern India and characterized the DPS coexisting in its RUI based on surveys of over 300 dairy producers.

2.2 Materials and methods

2.2.1 Research area

Capital of the southern Indian state of Karnataka, Bengaluru has a hot semi-arid climate (average maximum temperature 29.5°C, average minimum temperature 18.5°C, 948 mm of annual rainfall - monthly average 2013-2017, weather station data of the University of Agricultural Sciences Bangalore). The dry season (March-May) is followed by a monsoon season (June-October) and winter (November-February). Bengaluru's urban agglomeration is amongst the largest in India, driven since the 1970s by an unprecedent growth of population, which is now more than 10 million (Kumar et al., 2016; Verma et al., 2017). The state of Karnataka inaugurated its dairy development program as early as 1974, based on the model of Operation Flood, setting up the Karnataka Milk Federation (KMF; Alderman, 1987). Two research transects were established within Bengaluru's RUI, following an urban to rural gradient: the northern transect (Nsect) was a rectangular stripe of 5 km width and 40 km length along a north-south axis, starting 10 km away from the city centre, in the northern part of Bengaluru (Figure 2.1). The southern transect (Ssect) was a ca. 300 km^2 polygon along a south-west axis of 30 km length, starting 10 km away from the city centre, in the southern part of Bengaluru. Each settlement (village, suburb or urban neighbourhood) within the two transects was identified and assigned a survey stratification index (SSI) stratum. SSI went from stratum 1 = urban to 6 = rural, based on build-up density of the settlement and its distance to Bengaluru's centre as proxy for its urbanization level (Hoffmann et al., 2017). Urbanization levels were "urban" (strata 1 and 2), "peri-urban" (strata 3 and 4) and "rural" (strata 5 and 6; Hoffmann et al., 2017).

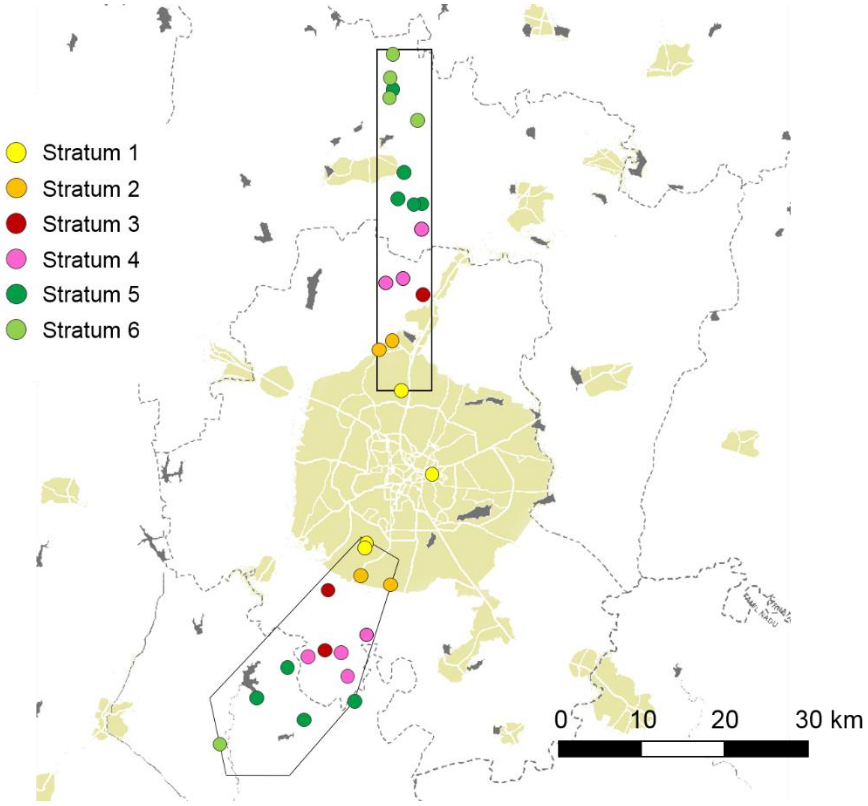

Figure 2.1 Map of Bengaluru (built-up area in colour), northern and southern research transects and selected settlements per stratum of the survey stratification index 1 = urban and 6 = rural.

2.2.2 Sampling design

A two-step random selection process was used to survey a minimum of 300 dairy producers across both transects: 30 settlements, 15 in Nsect and 15 in Ssect, were first drawn at random proportionally to the transect's prevalence of settlements per SSI stratum (Table 2.1; Hoffmann et al., 2017). In a second step, dairy producers were randomly selected per settlement, based on the latest vaccination list for foot-and-mouth disease[2]. In two urban settlements, the vaccination list was not available. Thus, the total number of dairy producers was assessed by scouting the settlement on foot and talking to local inhabitants. As Ssect was more urbanized than Nsect (Hoffmann et al., 2017) and to compensate for the lower number of dairy producers in urban settlements (9 ± 7 dairy producers) than in peri-urban (45 ± 37) and rural ones (55 ± 26, correlation coefficient SSI:total number of dairy producer per settlement = 0.55, $P < 0.05$), i) the selection threshold (ST) of dairy producers per settlement was set at 20% in Nsect and at 30% in Ssect; ii) two urban settlements were purposefully added, one in Nsect (stratum 2, ST = 20%, 2 surveys), and one close to the city centre, thus

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[2] Mandatory vaccination campaign done every 6 months, indicating the name of the cattle owner and number of vaccinated cattle (personal communication by local veterinarians).

mid-way between the two transects (stratum 1, ST = 30%, 4 surveys). To assure potentially continuous, even though minimal, involvement in milk marketing, only dairy producers with two or more dairy cattle considered as productive assets (LDH) were surveyed. Based on first insights from the field, dairy cattle considered as productive assets were: lactating (L) or dry (D) cows, plus mature heifers (H; pregnant or inseminated at least once), which were cared for in a similar way as cows, although not productive per se. By opposition, management of calves and immature heifers was extensive. Purebred *Bos taurus* Holstein Friesian (HF) and Jersey were considered as "exotic" genotypes, as opposed to "native" *Bos indicus* genotypes – mostly Hallikar, an indigenous draught breed from the State of Karnataka with low milk production potential (2.4 kg per day; National Dairy Development Board, 2015). The lack of breeding records prevented the distinction between different types of crossbreeds, despite dairy producers identifying some (multigeneration) crossbreeds as "All-Black" or "Half-Black". A total of 337 dairy producers were surveyed between mid-August and mid-November 2016 (59% in rural settlements, 33% in peri-urban and 8% in urban ones; Table 2.1).

Table 2.1 Number (n) of selected settlements and completed dairy production baseline surveys in the northern research transect (Nsect), in the southern research transect (Ssect) and in additional locations (Add.) per survey stratification index (SSI) stratum and urbanization level.

Urbanization level	SSI	Settlements (n)				Share
		Nsect	Ssect	Add.	Total	
Urban	Stratum 1	1	2	1	4	25%
	Stratum 2	1	2	1	4	
Peri-Urban	Stratum 3	1	2		3	31%
	Stratum 4	3	4		7	
Rural	Stratum 5	5	4		9	44%
	Stratum 6	4	1		5	
	Overall	15	15	2	32	
		Surveys (n)				Share
		Nsect[1]	Ssect[2]	Add.	Total	
Urban	Stratum 1	3	8	4[2]	15	9%
	Stratum 2	8	5	2[1]	15	
Peri-Urban	Stratum 3	13	13		26	33%
	Stratum 4	38	46		84	
Rural	Stratum 5	43	87		130	58%
	Stratum 6	45	22		67	
	Overall	150	181	6	337	

[1]selection threshold per settlement of 20%; [2]selection threshold per settlement of 30%.

2.2.1 Dairy production baseline survey

The interview-based dairy production baseline survey and its procedures were standardized during a pre-testing phase. All surveys were conducted in Kannada, the official language of the state of Karnataka, face-to-face with the dairy producer himself/herself or an adult member of his/her household (HH). Before starting the survey, the purpose and scope of the survey was explained and only respondents giving oral consent to participate were surveyed. Every survey was conducted by a team of two persons: one translator, familiar with the questions and one researcher, filling out the survey sheets while checking for plausibility and consistency of answers. One survey lasted for 28 minutes on average. Collected quantitative and qualitative data addressed the socio-economic profile of the dairy producer, dairy herd composition and management with focus on breeding, health care and feeding, in- and output markets for dairy production and further agricultural activities following Dossa et al. (2011) and Roessler et al. (2016; Table 2.2). Socio-economic classification of the HH followed standards of the Market Research Society of India (2011; Table 2.2). Calculations of HH labour force followed standards of the International Labour Organization (Table 2.2). Calculations of tropical livestock unit (TLU) used conversion factors as cited in Dossa et al. (2015; Table 2.2). Data were treated anonymously but the location of each dairy production unit (DPU) was georeferenced with a wireless GPS logger (Holux M-241), with priority given to the location of the cowshed if separated from the house of the dairy producer.

Table 2.2 Predictors and list of main variables collected in the dairy production baseline survey from 337 dairy producers in Bengaluru’s rural-urban interface or calculated from the answers.

Predictors	Type	Description
P-SSI	Ordinal	Settlement’s survey stratification index stratum as proxy for urbanization level of the DPU’s surroundings. 6 levels: stratum 1 = urban to stratum 6 = rural
P-GEN	Ordinal	Prevalence of exotic genotypes (Holstein Frisian and Jersey) within the herd as proxy for specialization in dairy production. 3 levels: “High” = a herd including exclusively exotic genotypes; “Medium” = a herd including crossbreeds and eventually exotic genotypes; “Low” = a herd including native genotypes and eventually crossbreeds or exotic genotypes or both
P-FLOW	Categorical	Types of cattle flows within the herd during the 12-month period preceding the survey; includes buying (inflow) and selling (outflow) of cattle. 4 categories: “Closed” = a herd with no cattle in- or outflow; “Balanced flow” = a herd with both cattle in- and outflow; “Positive flow” = a herd with only inflow; “Negative flow” = a herd with only outflow
P-PAS	Binary	Use of pasture through grazing: “yes” or “no”
P-FOR	Binary	Reliance, at least partial, on self-cultivated forages: “yes” or “no”
Variables	Type	Description
LOC_Transect	Categorical	Location of the DPU at transect’s scale: northern transect, southern transect
LOC_Settlement	Categorical	Location of the DPU at settlement’s scale: 32 settlements
HHH_sex	Binary	Sex of HHH: “male” or “female”
HHH_age	Numerical	Age of the HHH (years)
HHH_status	Categorical	Legal status of the HHH; 3 categories: single; married; other
HHH_education	Ordinal	Education level of the HHH; 7 levels: illiterate; literate/primary schooling; middle schooling; secondary schooling; higher secondary schooling; graduate; post-graduate (Market Research Society of India, 2011)
HHH_experience	Numerical	Years of experience of the HHH in dairy production (years)
HHH_background	Binary	Parents of HHH also owned cattle: “yes” or “no”
HH_member	Numerical	Total number of HH members (n)

DPU = dairy production unit; HHH = Household head; HH = household

HH_potential.labour	Numerical	Labour force of the HH, based on the total number of HH members and their age (labour force). Conversion factors: male between 16 and 55 = 1.0 labour, female between 16 and 55 and male of more than 55 = 0.75, female of more than 55 = 0.5 (International Labour Organization)
HH_dairy.labour	Numerical	Number of HH members involved in dairy production (n)
HH_hired.dairy.labour	Binary	Off-farm labour is hired for dairy production: “yes” or “no”
HH_off.farm	Binary	One or more member of the HH has an off-farm economic activity: “yes” or “no”
HH_off.farm.who	Categorical	If one or more HH’s member has an off-farm economic activity, relationship of the HH’s member having an off-farm economic activity to HHH; 4 categories: “is HHH”, “from older generation”; “from same generation”, “from younger generation”
HH_chief.earner	Binary	HHH is chief earner of the HH: “yes” or “no”
HH_chief.earner.education	Categorical	If chief earner is not HHH, education level of the HH’s chief earner; 7 levels: illiterate; literate/primary schooling; middle schooling; secondary schooling; higher secondary schooling; graduate; post-graduate (Market Research Society of India, 2011)
HH_n.item	Numerical	Total number of items owned in the HH (items, 0-11); includes: electric connection, ceiling fan, liquefied Petroleum gas stove, refrigerator, colour TV, two wheeler, washing machine, air conditioner, agricultural land, 4-wheels vehicle, computer (Market Research Society of India, 2011)
HH_SEC	Ordinal	Socio-economic classification of the HH based on education level of HH chief earner and total number of items owned; 12 levels (Market Research Society of India, 2011)
HH_dairy.as.income	Categorical	Importance of dairy production as an income; 4 categories: “only dairy as income”; “mix income including dairy as main income”; “mix income including dairy as complementary income”; “dairy production is not an income”
EXPENSES_ranking.importance	Ordinal	Which are the three main expenses related to dairy production (Buying of forages; buying of concentrates; health care; mating; land; labour); 3 levels: first expense = 3, second expense =2, third expense = 1 and not an expense = 0.
DAIRY_nLDH	Numerical	Total number of dairy cattle considered as productive asset, which includes lactating cow (L), dry cow (D) and mature heifer (H; inseminated at least once or pregnant)

HHH = Household head; HH = household

DAIRY_nTotal	Numerical	Total number of dairy cattle
DAIRY_Lactation	Numerical	Lactation number of each L or D
DAIRY_Genotype	Categorical	Genotype of each dairy cattle; 5 categories: “HF”, “Jersey”, “HF x Jersey”, “Exotic x native” and “native”
MATING	Categorical	Type of mating techniques used; 3 categories: “AI”; “natural mating” and “both”
AI_success	Binary	AI is always successful at first try: “yes” or “no”
AI_heifer	Binary	It is more difficult to make heifer pregnant through AI than cows: “yes” or “no”
HEALTH	Categorical	Type of health troubles during the 12 last months preceding the survey
PASTURE_time.per.day	Numerical	Time per day spent pasturing (hours)
PASTURE_type	Categorical	Type of pasture used
FORAGES_type	Categorical	Type of forages fed to the dairy herd
FORAGE_origin	Categorical	Origin of the forage fed to the dairy herd
FORAGE_diff.feeding	Binary	Is differential feeding practised: “yes” or “no”
CONCENTRATE	Binary	Is concentrate feed fed: “yes” or “no”
MILK_prod.per.cow	Numerical	Average daily milk production per cow (litre)
MILK_total.prod	Numerical	Average total daily milk production per DPU (litre)
MILK_HH.consumption	Numerical	Amount of milk kept per day for HH consumption
MILK_marketing.channels	Categorical	Type of marketing channels used by dairy producer
MILK_price	Numerical	Price paid in INR per litre of milk
LIVESTOCK	Category	Type, number and reason for keeping additional livestock
TLU	Continuous	Total number of owned tropical livestock unit (TLU; n). TLU conversion factors used: cattle = 0.80, sheep/goats = 0.10, pigs = 0.20, poultry = 0.01 (Dossa et al., 2015)
AGRICULTURE_size.land	Numerical	Size of agricultural land available per DPU
AGRICULTURE_type	Categorical	Type of other agricultural activity
AGRICULTURE_reason	Categorical	Reason for additional agricultural activity

DPU = dairy production unit; HH = household; HF = Holstein Frisian; AI = artificial insemination; INR = Indian rupee.

2.2.2 Statistical analyses

DPS within Bengaluru’ RUI were identified by the two-step cluster analysis (IBM SPSS Statistics 20) as it can simultaneously handle quantitative and qualitative variables following typologies done by Dossa et al. (2011) and Roessler et al. (2016). First, quantitative and qualitative variables relevant for dairy production according to expert knowledge were selected based on completeness, consistency and (frequency) distribution of the answers. Strongly correlated variables were excluded ($P < 0.01$, Pearson correlation coefficient > 0.7), resulting in 26 main independent variables selected. A pre-screening of the data through categorical principal component analysis excluded five variables accounting for little variability (loading score < 0.5 on components with eigenvalue > 1). Several clustering runs were explored with the remaining 21 variables. The number of clusters was restricted to 3 - 5 to avoid low and unbalanced numbers of DPU per cluster and allow for meaningful interpretation of the cluster solution as a base for further investigations. A four-cluster solution, based on 5 coherent predictors and a fair silhouette measure of cohesion (0.3), was finally chosen. In addition to descriptive statistics depicting arithmetic mean and standard deviation (±) for relevant variables, chi-squared and Kruskal-Wallis tests were used on non-clustering variables to describe each DPS. Post hoc tests used were Pearson residuals (threshold at ± 1.96) or pairwise Wilcoxon rank sum tests (Holm correction for pairwise comparison). Significance was declared at $P < 0.05$.

2.3 Results

2.3.1 Predictors of dairy production systems

The first out of the five predictors of DPS was the settlement’s SSI (P-SSI; predictor importance (pi) = 0.26) as proxy for the urbanization level of the dairy production unit’s surroundings (Table 2.2). The second and third predictors related to breeding management: P-GEN captured the prevalence of exotic genotypes in the entire dairy herd (LDH plus calves and immature heifer; pi = 0.07; Table 2.2). The ownership of exotic genotypes attested specialization in dairy production because of the higher financial investment needed to acquire and maintain high yielding cattle. A herd including exclusively exotic genotypes was thus given the specialization grade “high” (50% of all herds). A herd including crossbreeds and eventually exotic genotypes was given the specialization grade “medium” (36%). A herd including native genotypes and eventually crossbreeds or exotic genotypes or both was given the grade “low” (14%; Figure 2.2). P-FLOW captured the buying (inflow) and selling (outflow) of cattle within the herd during the 12-month period preceding the survey (pi = 0.51; Table 2.2). P-FLOW categorized each herd independently of the net flow and type of cattle, as follows: a herd with no cattle in- or outflow was classified “closed” (40% of all herds), a herd with both cattle in- and outflow had a “balanced flow” (17%), a herd with only inflow had a “positive flow” (15%) and a herd with only outflow had a “negative flow” (28%; Figure 2.2). The fourth and fifth predictors related to the feeding management: P-PAS captured the use of pasture through grazing (pi = 0.90; Table 2.2): “no” meant an absolute “absence of pasture” (25% of all herds), while “yes” meant “use of pasture” (75%; Figure 2.3), independently of the regularity and length of daily pasturing, and ignoring if the whole herd or only some cattle were sent to pasture or not. P-FOR captured the reliance, at least partial, on self-cultivated forages (pi = 1.00; Table 2.2): “no” meant that the dairy producer was not cultivating any forage (23% of all herds), while “yes” meant reliance on self-cultivated forages (green, dry or crop residues; 77%; Figure 2.3). Thereby no distinction was made between complete or partial reliance because i) the level of reliance on self-cultivated forage varied with season as did overall diet composition, ii) the origin of a given forage type could be multiple, and iii) crop use could be multiple.

2.3.2 Typology of dairy production systems

DPS-1: Extensive and ubiquitous. DPS-1 included 70 dairy producers (21%), from across the whole RUI: 39% were urban, accounting for 27 out of the 30 urban dairy producers surveyed overall ($P < 0.5$), 31% were peri-urban and 30% were rural (Figure 2.2). The breeding management of DPS-1 mostly followed the overall trend of a dairy herd including exotic genotypes and crossbreeds, and no selling or buying of cattle (Figure 2.2). The feeding management of DPS-1 relied on the use of pasture ($P < 0.05$) but not on self-cultivated forages ($P < 0.05$; Figure 2.3). DPS-1 was thus characterized as an extensive ubiquitous DPS.

DPS-2: Semi-intensive and rural with closed specialized herds. Being the largest amongst the four clusters, DPS-2 included 120 dairy producers (35%) but none from an urban settlement ($P < 0.05$; Figure 2.2). More than one dairy producer out of two kept exclusively exotic genotypes ($P < 0.05$) in a closed herd ($P < 0.05$; Figure 2.2). The feeding management of DPS-2 incorporated both the use of pasture ($P < 0.05$) and the reliance, at least partial, on self-cultivated forages ($P < 0.05$; Figure 2.3). DPS-2 was thus characterized as a semi-intensive rural DPS with closed specialized herds.

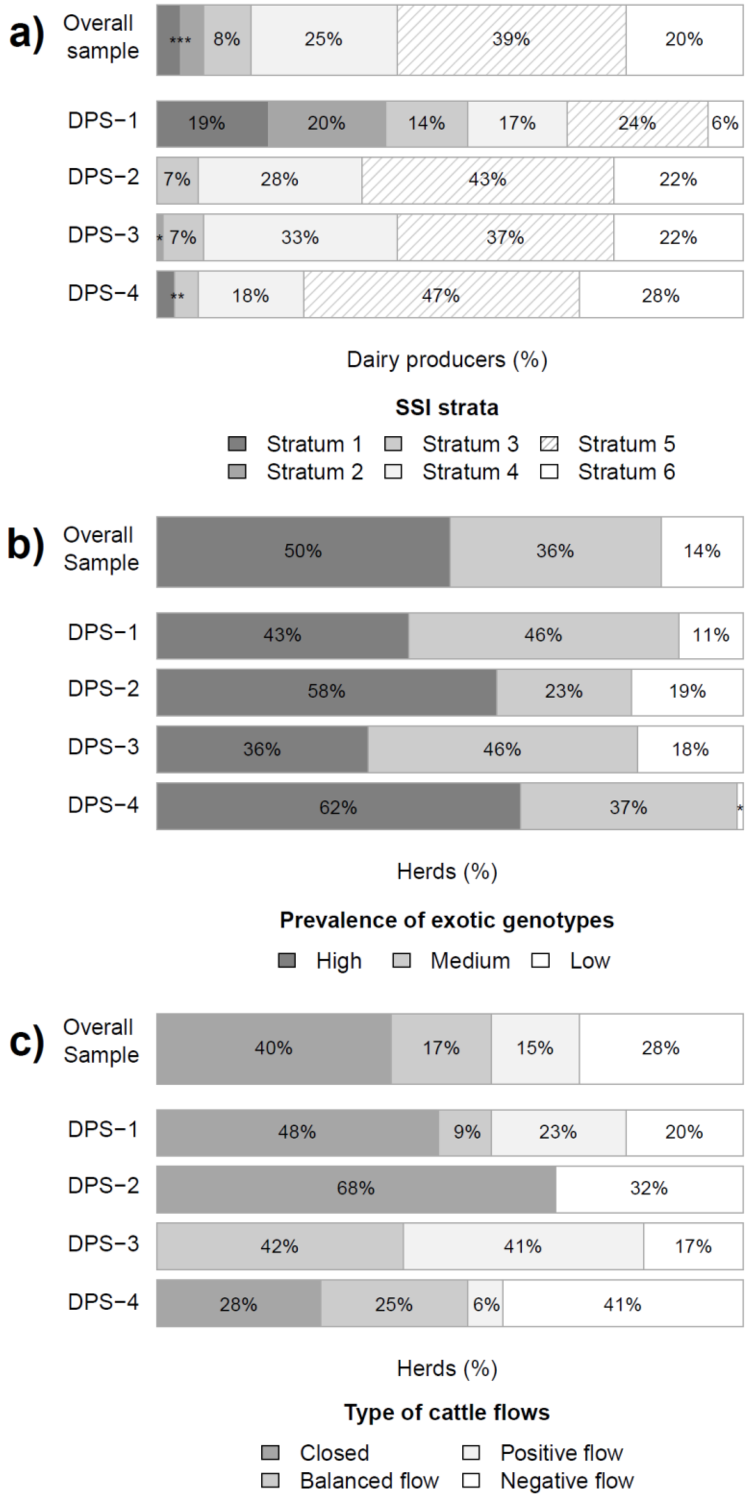

Figure 2.2 Frequency of a) dairy producers (%) according to the urbanization level of the dairy production unit's surroundings (P-SSI) overall and for each dairy production system (DPS) with survey stratification index (SSI) stratum 1 = urban to stratum 6 = rural.
* = 1% for DPS-3 stratum 2; ** 3% for DPS-4 stratum 1 and 4% for DPS-4 stratum 3; *** = 4% each for stratum 1 and 2 in the overall sample
b) prevalence of exotic genotypes within the herd (P-GEN) overall and for each DPS.
* = 1% for DPS-4, low prevalence.
c) type of cattle flows within the herd (P-FLOW) overall and for each DPS.

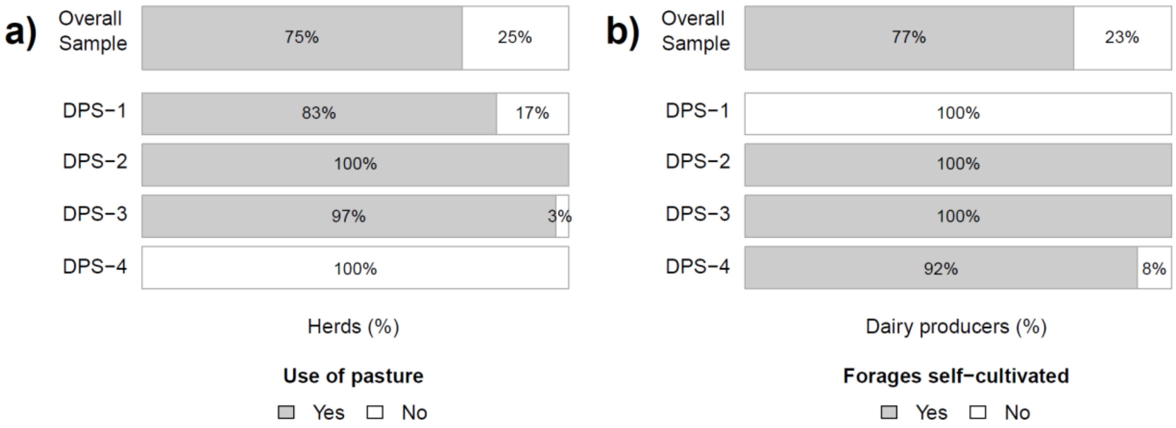

Figure 2.3 Frequency of a) herds (%) according to their use of pasture through grazing (P-PAS) and b) dairy producers according to their reliance, at least partial, on self-cultivated forages (P-FOR) overall and for each dairy production system (DPS).

DPS-3: Semi-intensive and rural with dynamic herds. DPS-3 included 76 dairy producers (23%) of which 59% were rural (Figure 2.2). In contrast to DPS-2, dairy producers in DPS-3 kept mostly exotic genotypes and crossbreeds ($P < 0.05$). Cattle flows were high since all dairy producers either bought (42%; $P < 0.05$) or sold (17%) cattle, or had been involved in both activities (41%) during the 12 months preceding the survey ($P < 0.05$; Figure 2.2). The feeding management of DPS-3 equated that of DPS-2 and incorporated use of pasture ($P < 0.5$) as well as reliance, at least partial, on self-cultivated forages ($P < 0.05$; Figure 2.3). DPS-3 was thus characterized as a semi-intensive rural DPS with dynamic herds.

DPS-4: Intensive and rural with specialized herds. DPS-4 included 71 dairy producers (21%) of which 75% were rural (Figure 2.2). DPS-4 had the largest share of dairy producers keeping only exotic genotypes (62%, and only 1% showing low specialisation of the herd; $P < 0.05$) but also the largest share of herds with a negative flow (41%; $P < 0.05$; Figure 2.2). The feeding management of DPS-4 was the only one not relying on pasture ($P < 0.05$) but only, at least partially, on self-cultivated forages ($P < 0.05$; Figure 2.3). DPS-4 was thus characterized as an intensive rural DPS with specialized herds.

2.3.3 Characteristics of dairy productions systems

Additional spatial patterns. Despite P-SSI accounting for location within Bengaluru's RUI, DPS displayed additional spatial patterns: at the transects' scale, DPS-4 was more common in the Nsect than in the Ssect ($P < 0.05$). Anecdotic data suggested that the Nsect was drier than the Sect, potentially leading to less Nsect dairy producers sending their cattle to pasture because of reduced biomass availability or higher risk of heat stress due to the warmer environment or both. At the settlements' scale, DPU of a same settlement were often regrouped in the same DPS ($P < 0.05$) even in rural areas where more than one DPS existed, showing that conditions even at settlement level impacted resources available to dairy producers.

Socio-economic profile of dairy producers. The socio-economic profile of Bengaluru's DPU was homogenous across the four DPS and provided a clear picture of the local dairy sector: in Bengaluru, dairy production was a *family business*, with the household head (HHH) typically being a married man, 53 ± 13 years old, with not more than the mandatory school education but 22 ± 14 years of experience in dairy production, whose parents also had owned cattle (79% of HHH). He was chief earner of the HH (74%), which included 4 ± 2 additional members, often spread across three generations. Labour force of the HH amounted to 3.6 ± 1.6. Including the HHH, 3 ± 2 HH members were involved in dairy production, but their amount of work varied. Only 4% of the DPU hired extra labour, corroborated by a low importance ranking (0 ± 0.2) of labour as expenses related to dairy production (Table 2.3). On 53% of the DPU, one or more HH members (1.4 ± 0.6; in 66% of the cases a member of the younger generation) was involved in an off-farm economic activity. 66% of the HH classified as *middle class,* whereby the importance of dairy production as an income source differed among DPS: whereas the majority of DPU in DPS-3 and DPS-4 had mixed income sources with dairy production as the major (44% of DPU) or complementary source (37%), in DPS-1 dairy production was the only income source of 36% of the DPU ($P < 0.05$). In contrast, dairy production was an unimportant income source for 12% of DPU in DPS-2 ($P < 0.05$).

Table 2.3 Importance ranking scores of expenses related to dairy production with 3 = first expense, 2 = second expense, 1 = third expense and 0 = not an expense.

DPS	Importance ranking score					
	Concentrate feed	Forages	Health care	Reproduction	Land	Labour
DPS-1	2.8 ± 0.6	1.5 ± 1.1^{a}	0.5 ± 0.8	0.1 ± 0.5*	0	0
DPS-2	2.7 ± 0.9	0.8 ± 1.1^{b}	0.7 ± 0.9	0.2 ± 0.6*	0 ± 0.3	0
DPS-3	2.7 ± 0.9	0.7 ± 1.0^{b}	0.7 ± 1.0	0.1 ± 0.4*	0 ± 0.1	0
DPS-4	2.9 ± 0.5	0.8 ± 1.0^{b}	0.5 ± 0.8	0 ± 0.1*	0 ± 0.2	0 ± 0.2

Values within a column with different subscript letters differs significantly ($P < 0.05$).
*Significant analysis of variance but data is not enough to make statements about pairwise differences.

Dairy herd. With minor variations across the four DPS, insights on dairy herd further completed the overview of Bengaluru's dairy sector as a *small-scale* family business: the average LDH number was 3 ± 2 with 1 ± 1 additional calves and/or immature heifers kept for herd renewal. Large herds were rare with only 4 DPU in the whole sample owning more than 10 LDH. The average lactation number differed between the DPS: in DPS-3 with its dynamic breeding management of in- and outflow, the average lactation number was 2.1 ± 1.0, as compared to 2.6 ± 1.1 in DPS-2 ($P < 0.05$), where no selling and/or buying of cattle took place and cattle were thus kept longer. Cattle in DPS-1 and DPS-4 had an identical intermediate lactation number (2.3 ± 0.9).

Breeding, reproduction and health care. As captured by P-GEN, exotic genotypes were standard in Bengaluru' RUI across all DPS with overall more than one dairy cattle out of two being HF (54% of all dairy cattle) and at least one out of 6 being Jersey (15%). Despite the advantage of selling male calves for draught purpose, native cattle were the least common (10%); they were kept for both milk production and draught purpose (45%) or exclusively for milk production (55%). Crossbreeds (21%), from first-generation *HF x Jersey* or *exotic x native* to multigeneration indiscriminate crossbreeds, resulted from local breeding practices rather than being a real choice: artificial insemination (AI) was made widely available by KMF and across the four DPS, 86% of all DPU relied exclusively on AI and 9% on both AI and natural mating (NM) if their first choice method failed or according to the cattle genotype. The usage was to inseminate heifers with Jersey semen, irrespective of their own genotype, to facilitate their first calving, which explained numerous HF x Jersey crossbreeds. The success of AI however varied amongst the DPS: only 18% of DPU in DPS-3 stated that the first AI was always successful, by opposition to 35% in DPS-1, 30% in DPS-2 and 42% in DPS-4 ($P < 0.05$). Most DPU did not rely on NM due to lack of available bulls, especially of exotic genotypes, which further explained reliance on AI and exotic x native crossbreeding[3]. DPU in DPS-4 were more successful in renewing their herd with only 19% of them stating it was harder to get a heifer pregnant than a cow (*versus* 44% in DPS-1, 35% in DPS-2 and 38% in DPS-3; $P < 0.05$) and getting them pregnant at 21 ± 8 months old (*versus* 27 ± 9 in DPS-1 and 27 ± 11 in DPS-2; $P < 0.05$; 24 ± 10 in DPS-3). Despite (repeated) use of AI, dairy producers did not consider reproduction costs among their three main expenses (importance

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[3] Anecdotic information suggests that in the city bulls are freely roaming around, and three urban DPU had no mating strategy other than letting nature follow its course with their cows pasturing in the streets.

ranking = 0.1 ± 0.5; Table 2.3) as they benefited from AI at a subsidised price through the dairy cooperatives.

Health problems were irrespective of DPS too: one farmer out of four reported mastitis in his herd during the last 12 months, even though the cows' udder was washed before milking on all farms. Moreover, 35% of the dairy producers reported additional health issues such as fever (50% of additional health issues), foot-and-mouth disease (12%, despite vaccination campaigns every 6 months[4]), physical wounds (11%) and fertility or calving issues or both (11%). Hoof care was uncommon (5% of all DPU) as was the use of bedding material (rubber mats) in the cowshed (7%). Because of the high costs engendered by a single health problem, dairy producers considered health care among their three main expenses (importance ranking = 0.6 ± 0.9; Table 2.3).

Nutrition. As captured by P-PAS, overall 3 DPU out of 4 made use of pasture: typically, the whole dairy herd, apart from the calves, was sent to pasture once per day. In line with their extensive feed management, pasturing lasted the longest with 6.6 ± 1.6 hours per day in DPS-1 ($P < 0.05$), mostly on public grounds (80%; $P < 0.05$) or shared pasture (9%; $P < 0.05$). In comparison, pasturing lasted 5.9 ± 1.3 hours in DPS-2 and 5.5 ± 1.5 in DPS-3 and the type of pasture used was more diverse: public grounds (DPS-2 = 49%; DPS-3 = 33%), shared pasture (DPS-2 = 3%; DPS-3 = 0%), public grounds in addition to their own pasture (DPS-2 = 28%; DPS-3 = 37%) or exclusively on their own pasture (DPS-2 = 20%; DPS-3 = 30%).

Nevertheless, no DPU relied solely on pasture and, as captured by P-FOR, 77% of them also relied, at least partially, on self-cultivated forages. Most farmers stated that they usually relied exclusively on their own production (DPS-2 = 60%, DPS-3 = 67%, DPS-4 = 68%) but 43% nonetheless had to buy forages during the last 12 months because of forage shortage. Only 9% of DPU sold forage during the last 12 months. Common cultivated green forages were African tall maize (*Zea mays*; cultivated by 81% of DPU in DPS-2, DPS-3 and DPS-4) and hybrid Napier grass (*Pennisetum glaucum* × *P. purpureum*; cultivated by 80%; Table 2.4; Figure 2.6). Although not cultivating forages, 50% of the DPU in DPS-1 either bought (86%) or got African tall maize for free (14%; agreement or exchange with a neighbour, or collected from public grounds). 50% of the DPU in DPS-1 also either bought (79%) or got hybrid Napier grass for free (21%). Consequently, expenditures for forages were frequently mentioned as relevant in DPS-1 (importance ranking = 1.5 ± 1.1; DPS-1 *versus* DPS-2, DPS-

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[4] Anecdotic information suggests that dairy producers did not systematically vaccinate pregnant cows or mature heifers by fear of affecting their pregnancy.

3 and DPS-4; P < 0.05; Table 2.3). In addition to these common green forages, 39% of the DPU in DPS-1, DPS-2 and DPS-3 fed their cattle with “wild grasses”: a mix of grasses naturally available in the area, collected for free on their own non-cultivated land (e.g., from field margins) or public grounds (e.g., lakes shores, including lakes in urban areas). Only 21% of the dairy producers in DPS-4 fed wild grasses to their cattle (P < 0.05), once more in line with their more intensive feeding management (Table 2.4). Across the four DPS, 83% of the farmers relied on straw of finger millet (*Eleusine coracanal*, known locally as *ragi*) as forage during the dry season (Figure 2.5), while rice straw feeding was uncommon (3%). Less frequently used forages were fresh finger millet stems, sorghum (*Sorghum bicolor*) and, in urban areas, organic waste from fruit and vegetable markets. As DPS-4 dairy producers did not send their cattle to pasture, they fed them more often than the other dairy producers (4.6 ± 2.1 times per day *versus* 2.5 ± 1.4 in DPS-1, DPS-2 and DPS-3; P < 0.05). Across DPS, only 12% of all dairy producers practiced a differential feeding of forages based on physiological status of LDH. Dairy producers in DPS-2, DPS-3 and DPS-4 usually chopped forages offered to the dairy herd with a sickle (60%) while the use of a chaff cutter was rare (10% in DPS-4; P < 0.05). A large range of concentrate feed was available on the surveyed DPU, either as single element or as a mixture of wheat flour, with or without bran, corn flour, dairy pellets, chickpea husks (*Cicer arietinum*, known as “Bengal gram”) and groundnut cake, to which 85% of the farmers added salt or a commercial mineral supplement (Figure 2.4). Although the dairy cooperatives provided some concentrate feed at a subsidised price, concentrate feed was mentioned by all dairy producers as their main expense, with an average importance ranking of 2.8 ± 0.8 (Table 2.3). Concentrate feed was fed twice a day, whereby the amounts were adjusted to the individual animal’s physiological status. Feeding the HH’s kitchen wastes to cattle was common for 86% of DPU in DPS-1, DPS-2 and DPS-3 but less frequent in DPS-4 (69%; P < 0.05). No cattle had *ad libitum* access to water, and they were mostly offered water in the shed (82% of all herds) or in addition had access to water during pasture (river, pond, lake, 15%).

Milk production and marketing. Milk production per DPU and day was highest in DPS-3 and DPS-4 and lowest in DPS-2 (P < 0.05), while DPS-1 was in-between (Table 2.5). As each DPU kept 2.1 ± 1.3 lactating cows (only 5 dairy units had 5 to maximum 9 lactating cows at once), average daily milk production per cow made the difference, with cows in DPS-4 producing the highest amount of milk per day. Cows producing least were found in DPS-1 and DPS-2 (P < 0.05), while cows in DPS-3 had an intermediary production (Table 2.5). Milking other than by hand, which was a time-consuming task and constrained by the dairy cooperative's opening hours, was uncommon as only 9 DPU owned a milking machine. Dairy producers could not estimate the average lactation length within their herd because they usually stopped milking a cow when 7 months pregnant, irrespective of the duration of lactation. Therefore, the duration of the lactation period depended on the time a cow needed to become pregnant again, was strongly variable and, as usually more than one AI was needed, rather long than short. Dairy producers in DPS-4 preferred to feed calves with milk from a bucket (65%) instead of having it suckle the cow, whereas most dairy producers in the other DPS allowed the calves to suckle the dam (avg. across DPS-1, DPS-2 and DPS-3 = 62%; $P < 0.05$). In line with the different approaches, weaning occurred faster in DPS-4 (3.6 ± 1.3 months) than in all other DPS (4.6 ± 2.6 months; $P < 0.05$).

DPU usually kept 1.2 ± 0.9 L of milk per day for their own consumption; since DPU in DPS-2 had a low total daily milk production, they kept in proportion a share twice as high as DPU from the other DPS ($P < 0.05$; Table 2.5). Since no DPU owned a cold storage facility nor processed milk into dairy products to sell them, any milk not used for household consumption was sold as raw milk. With the exception of 8% of DPU in DPS-2 who did not sell any of the produced milk ($P < 0.05$; Table 2.5), all other DP marketed milk either through dairy cooperatives linked to KMF or informal (direct) marketing channels, namely middlemen (usually delivering in bulk to restaurants) or directly to the consumer (Table 2.5). Across the rural DPS-2, DPS-3 and DPS-4, 83% of all DPU delivered their milk only to their dairy cooperative; 10% delivered to their dairy cooperative and sold some litres directly to their neighbours. In DPS-1 only 59% of DPU delivered exclusively to a dairy cooperative; since many DPU were located in (peri-)urban areas, they had easier access to a larger number of consumers: 14% sold their whole milk production through informal marketing channel(s) ($P < 0.05$), and 23% sold part of the milk informally and relied on a cooperative for the remaining milk ($P < 0.05$). The dairy cooperative network was very dense - for 95% of all DPU delivering milk to a dairy cooperative, the collection centre was located within the same settlement as the DPU. In addition to being able to easily deliver any quantity of milk twice daily on foot, dairy producers benefited from a subsidy of four Indian rupees (INR) per litre of milk in addition to an average milk price of 23 ± 1 INR per litre[5], which was based on the milk fat content. Informal milk marketing to middlemen and consumers yielded 31 ± 5 INR per litre[6]. The higher price and the access to consumers were the main drivers for direct milk marketing, while only four of the informal sellers claimed that they had no access to a dairy cooperative.

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[5] 23 INR + 4 INR subsidy = 0.36 Euro per litre of milk, at the time of the survey.

[6] 0.42 Euro per litre of milk, at the time of the survey.

Table 2.4 Feeding frequency (in % of DPU) for the most common forages and concentrate feed utilised in Bengaluru's dairy production systems (DPS), and their most frequent origin (own production (Own prod.), bought (Bought), collected for free from public grounds or as waste (Free) or collected on own ground but not cultivated (Wild)).

DPS	n	African tall maize		Hybrid Napier grass		Wild grass		Ragi straw		Concentrate feeds
		% of DPU	Origin	% of DPU	Origin	% of DPU	Origin	% of DPU	Origin	% of DPU
DPS-1	70	54*	Bought (86%*)	56	Bought (79%*)	37	Free (92%)	76	Bought (92%*)	100
DPS-2	120	83	Own prod. (81%)	70	Own prod. (81%)	41	Free (55%)	88	Own prod. (86%*)	100
DPS-3	76	89	Own prod. (82%)	76	Own prod. (81%)	39	Free (66%)	84	Own prod. (81%)	100
DPS-4	71	93	Own prod. (78%)	86	Own prod. (79%)	21*	Wild (63%)	82	Own prod. (78 %)	100

*Frequency differs significantly from overall frequency ($P < 0.05$).

Table 2.5 Daily milk production per dairy production unit (DPU) and per cow, share of milk kept for HH consumption and use of marketing channels by the dairy producers (DP).

DPS	n	DPU production (L milk DPU^{-1} day^{-1})	Cow production (L milk day^{-1})	% kept for HH consumption	Milk marketing (% of DP)			
					No milk sold	Dairy coop.	Informal	Mixed
DPS-1	70	20.5 ± 17.9^{ab}	8.2 ± 4.4^{a}	8 ± 12^{a}	4	59	14*	23*
DPS-2	120	13.6 ± 10.7^{a}	7.3 ± 3.9^{a}	18 ± 28^{b}	8*	80	2	10
DPS-3	76	18.7 ± 12.3^{b}	8.6 ± 3.7^{ab}	11 ± 19^{a}	1	84	3	12
DPS-4	71	24.5 ± 23.1^{b}	9.9 ± 4.3^{b}	7 ± 6^{a}	1	88	1	10

Values within a column with different superscript letters differ significantly from overall frequency ($P < 0.05$).

*Frequency within a column differs significantly from overall frequency ($P < 0.05$).

Figure 2.6 Bundles of Napier grass (left) and maize (right), the two most common green forages fed in Bengaluru's RUI.

Figure 2.5 Stack of ragi straw stored for the dry season. In front, another crop is drying.

Figure 2.4 Preparation of a concentrate ration from different types of concentrate feeds and salt.

Other livestock and agricultural activity. Cattle ownership exclusively for draught purpose was uncommon (8% of all DPU) and buffalo ownership was rare (3%). Livestock other than cattle was encountered on 50% of the surveyed DPU, namely sheep and goats (kept for meat) as well as chickens (kept for eggs and meat). The number of additional livestock kept was however low, accounting for only 0.22 ± 0.74 TLU owned per HH out of 3.35 ± 1.93 owned per HH in total. This additional livestock was often exclusively kept for HH consumption (46%) or for both HH consumption and sale (37%) but seldom exclusively for sale (17%). Next to dairy production, 84% of DPU in DPS-2, DPS-3 and DPS-4 but only 13% in DPS-1 ($P < 0.05$) pursued an agricultural activity. The latter 13% accounted for 9 out of 10 DPU across all DPS farms that cultivated crops but no forages for their cattle. Generally, one DPU out of two was producing crops only for its own HH consumption. Only DPU in DPS-4 were more commercially oriented, with 23% cultivating crop solely for selling ($P < 0.05$), 39% for selling in addition to HH consumption and only 38% exclusively for HH consumption. On average 1.6 ± 1.0 crops were cultivated, ranging from finger millet and all kinds of vegetables, fruits and flowers to mulberry for sericulture. The size of cultivated land averaged 1.03 ± 1.35 hectares and in 91% of the cases the cultivated land belonged to the farmer. Only 2% of all dairy producers rented additional areas and 7% cultivated land they did not own (sometimes in exchange for a part of the crops' or forages' yield; corroborated by a low importance ranking (0 ± 0.1) of land as expenses related to dairy production; Table 2.3). All dairy producers pursuing an agricultural activity also used their cattle manure, stored on a dung heap or in a pit, as organic fertilizer for their fields. Since most DPS-1 dairy producers did not cultivate land, 65% sold their manure ($P < 0.05$) and 13% gave it away for free, exchanged or discarded it ($P < 0.05$), with the remaining 9% mentioning several uses. While manure management in rural and peri-urban areas was homogenous across DPS, alternative manure management turned up in urban areas, where space for dung heaps was lacking: some urban dairy producers stored fresh manure only a few days or produced dry dung cakes before selling, giving or exchanging it; in case manure was discarded it was washed to the sewer system.

2.4 Discussion

The analysis of dairy production within the RUI of the emerging megacity of Bengaluru provided interesting insights on the diversity of small-scale dairy production systems that supply a growing population of several million milk consumers, on their spatial distribution and on potential linkages between SES components along rural to urban gradients.

A first relevant point to discuss is Bengaluru's dairy sector, especially its overall homogeneity and its successful network of dairy cooperatives. In contrast to the immense scale of Bengaluru as a city, its dairy sector relies on numerous small-scale family businesses with a homogenous socio-economic profile. In India, 80% of dairy animals are kept in herds of 2 to 5 cows (Cunningham, 2009), a range in which Bengaluru's average number of LDH per HH (3.0 ± 1.5) fitted. Cattle and livestock ownership per HH was however lower than in West African (peri-)urban areas (Amadou et al., 2012; Roessler et al., 2016), which can be related to the high share of vegetarians in India and their focus on dairy products as source of animal protein (Government of India, 2014). While higher numbers of TLU were reported for peri-urban than for urban HH in Bobo Dioulasso, Burkina Faso (Dossa et al., 2015), Bengaluru's urban DPU owned more TLU than peri-urban or rural ones. The average daily milk production per cow of 8.3 L was above the average of 5.9 L milk per day reported for the district of Bengaluru Urban (National Dairy Development Board, 2015) but similar to milk yields of exotic crossbreeds in a typical four-dairy-animal farm in Haryana state, northern India (7.5 L milk per day; Hemme et al., 2003) or in Ouagadougou, capital of Burkina Faso (6.7 to 11.0 L milk per day; Schlecht et al., 2019). Another Indian dairy production characteristic is the reliance on family labour (Cunningham, 2009; Hemme et al., 2003) as seen in Bengaluru, while in contrast, one out of three urban dairy producers in Ethiopia hired labour (D'Haene and D'Haese, 2019). The trade-off between family labour and intensification of production is documented for rural Ethiopia (Chagwiza et al., 2016) while in Nakuru, Kenya, dairy producers trade-off family labour having an off-farm monetary activity for hired labour (Migose et al., 2018). In Bengaluru, the number of LDH correlated positively but weakly to HH available labour force (Pearson correlation coefficient = 0.11; $P < 0.05$). As new job opportunities are available in the city, especially for a younger better-educated generation (Satterthwaite et al., 2010), such a trade-off might partly explain the lower number of dairy producers in urban areas as seen in Bengaluru and deserves more research, especially since farm persistence in and adaptations to an urbanizing environment are linked to internal family dynamics (Inwood and Sharp, 2012). Similarity in number of cattle owned and reliance on family labour was reflected in the homogenous socio-economic profile of the DPU. The classification of most of Bengaluru's dairy producers as middle class (Market Research Society of India, 2011), to which off-farm income certainly contributed, certified a good economic situation at the country level as this scale is national. It might however not realistically reflect dairy producers' economic power in comparison to other inhabitants of Bengaluru as consumption inequality is generally more pronounced in urban areas (Anand and Thampi, 2016). Overall, Bengaluru's dairy sector was not only homogenous for most of the production practices – herd management, breeding, health care - but also well-established, thanks to its successful network of dairy cooperatives linked to KMF: a milk collection centre existed in nearly all urban, peri-urban and rural settlements, and provided dairy producers with inputs such as exotic genotypes through AI, health check-ups, concentrate feed, and extension services to improve their production. In rural Ethiopia, cows owned by members of a dairy cooperative yielded 8.3 L milk per day as compared to 4.3 L milk per day for non-members (Chagwiza et al., 2016). For 95% of all DPU across the whole RUI, the dairy cooperatives served as the marketing channel for all or a part of their milk production, thereby fulfilling their role in scaling-up milk collection, processing and marketing to urban areas (Cunningham, 2009). Through its dairy cooperative, Bengaluru nurtured the intensification of its dairy sector by easing access to new inputs (exotic genotypes, concentrate feed; Chagwiza et al., 2016; Duncan et al., 2013).

A second relevant point to discuss is the existence of distinct DPS coexisting in Bengaluru's RUI and the predictors they are based on. Regarding the topic of urbanization, the consideration of rural areas as one urbanization level shifted the focus from livestock production systems in (peri-)urban areas (Amadou et al., 2012; Dossa et al., 2015; Roessler et al., 2016) to livestock production systems in an urbanizing environment. Additionally, the consideration of urbanization level as a predictor highlighted the spatial pattern of DPS across Bengaluru's RUI but also its relative importance in shaping them. On one hand, the ubiquitousness of DPS-1 showed that a specific set of constraints *versus* opportunities in resource availability for dairy producers, namely the non-cultivation of forages *versus* public grounds available for pasture or forages collection or both, existed across urbanization levels. Reliance of urban dairy farmers on public lands and organic market wastes is known from India (Prasad et al., 2019). In Bobo Dioulasso, Burkina Faso, "landless" urban cattle production systems relying on extensive pasturing on public grounds also exist, while crop-livestock integration is maintained by other cattle production in (peri-)urban areas (Dossa et al., 2015). Interestingly, the ubiquitousness of DPS-1 showed that reliance on public lands was an extensification rather than intensification strategy pursued also by rural DPU, which could be linked to issues of land accessibility (Bah et al., 2003) or family labour (Chagwiza et al., 2016; Inwood and Sharp, 2012; Migose et al., 2018; Satterthwaite et al., 2010). On the other hand, three DPS coexisted in rural areas, highlighting a diversity of production strategies and specific set of constraints *versus* opportunities in resource availability for dairy producers even at the same urbanization level. As improved animal nutrition and genetics are the most effective steps to improve – and intensify – dairy production (Chagwiza et al., 2016; Mayberry et al., 2017), predictors related to nutrition and breeding allowed to assess the intensification level of the four DPS. In Burkina Faso and Ghana, distinct intensification levels existed within (peri-)urban areas (Dossa et al., 2015; Roessler et al., 2016). In Bengaluru, differences in intensification level were strongest in peri-urban and rural areas with DPU classified from extensive to intensive, while the majority of urban DPU were extensive. Concerning nutrition, buying of forage is commonly seen as an step toward intensification (Chagwiza et al., 2016) but in the context of urbanization, also as a consequence of decoupling of crop-livestock production: e.g., urban DPU in Jimma, Ethiopia or Cairo, Egypt, bought green forages or increased the share of other feedstuffs to cope with land shortage (Daburon et al., 2017; Duguma and Janssens, 2016). This was however uncommon in Bengaluru's urban areas because most DPU relied on use of pasture, collected forages from public grounds or organic wastes or used all these strategies to complement feed intake at the homestead. Concerning breeding, cattle flows also differed across DPS in Mekelle, Ethiopia (D'Haene and D'Haese, 2019) and in Cairo, Egypt, evolved as an adaptation strategy to the pressure of urbanization (Daburon et al., 2017). Specialised dairy cattle genotypes, mostly purebred animals, were dominant across Bengaluru's RUI, which was also the case in Jimma, Ethiopia (D'Haene and D'Haese, 2019), while in Ouagadougou, Burkina Faso, European crossbreeds coexisted with zebu breeds (Schlecht et al., 2019).

A third important point to discuss are the potential linkages between social-ecological components of Bengaluru's DPS. The main linkage between producers and consumers is the exchange of milk as a material flow against a financial one. Urbanization level however impacted producer-consumer linkages as milk flowed from peri-urban and rural producers towards Bengaluru's (peri-)urban consumers through the intermediary of KMF, thus structurally distancing them (Butler, 2012; Lamine, 2015; Sundkvist et al., 2005). Vertical and horizontal integration of Bengaluru's formal dairy value chain was strong, as KMF dominated rural milk collection to urban distribution of dairy products. Producer-consumer linkages in urban areas were diverse, ranging from informal direct customer linkage (neighbours) to informal indirect (restaurant through middleman) and formal indirect ones (dairy cooperatives), which reflected the general diversity of India's dairy sector (Cunningham, 2009; Prasad et al., 2019). As in Nakuru, Kenya (Migose et al., 2018), informal urban channels in Bengaluru were financially more rewarding. Producer-consumer linkages in urban areas were further strengthen by the consumers' preference for fresh raw milk over processed milk, awareness of health risks of raw milk - thus boiling freshly sourced milk before consumption - and higher trust in a direct producer-consumer linkage (Lapar et al., 2010). At last, producer-consumer linkages in urban areas were strengthened by the socio-cultural services provided by cows to Bengaluru's population: as a holy animal, their presence is enjoyed and they are still part of many religious ceremonies e.g. blessing of a new house (Kennedy et al., 2018; Narayan, 2018). Urban milk collection points of the cooperatives were less easily accessible than rural ones (not accessible by foot) and served as backup to sell milk leftovers, while the accessibility to provided inputs (AI, veterinary care, concentrate feed) was more variable. Urban dairy production in Bengaluru thus not only provided fresh milk for consumers but also an opportunity for dairy farmers to continue their economic activity in a city that literally grew around them, as seen in 19th century London (Atkins, 1977), while integrating themselves into the urban landscape, benefitting from improved infrastructure (schools, hospitals) and preserving their cultural identity (Lerner and Eakin, 2011). Cattle are however paying the price of this urban integration as they are not well-adapted to urban husbandry conditions (Pinto et al., 2020; Prasad et al., 2019), and are at risk of ingesting plastic waste on the many uncontrolled waste dumps when foraging in the streets (Kennedy et al., 2018; Vohra, 2012). The most important difference between rural and urban SES linkages at farm-level related to manure and the decoupling of crop-livestock production in urban areas. Not only did Bengaluru act as a nutrient sink (Drechsel et al., 2007) but the manure was sometimes washed away to avoid neighbours' complaints about bad odour and flies (Butler, 2012; Prasad et al., 2019), potentially polluting Bengaluru's water bodies (Prasad et al., 2019). The (negative) environmental consequences of decoupling dairy production from agricultural land thus represent the biggest weakening of SES linkages, as the feedback between the polluted environment and the consumers is too weak, preventing the correction of dairy management practices. Such gaps should be filled by institutions (Termeer et al., 2019). At landscape-level, the extensive strategy of urban dairy producers trades off a social benefit - the integration of dairy producers within Bengaluru – for a negative externality - manure mismanagement - and poor husbandry conditions.

2.5 Conclusions

The case study of dairy production in the urbanizing environment of Bengaluru's rural-urban interface demonstrates that distinct dairy production systems coexist along a rural-urban gradient. Addressing the urbanization level as a parameter reveals spatially explicit trends of intensification as well as social-ecological linkages in the form of material, information and financial flows. Despite rapidly progressing urbanization and a population of

10 million, Bengaluru's dairy sector relies on small-scale family dairy production units and a strong network of dairy cooperatives connecting dairy producers in remote rural settlements to the urban consumers, thereby sustaining dairy production and livelihood of the producers. Distinct feeding and breeding practices result in several intensification levels across Bengaluru's rural-urban interface. Shifts in resources availability, especially labour, are potential drivers of intensification but also of active extensification of market-oriented dairy production in an urbanizing environment. Urbanization level itself leads to distinct social-ecological linkages. Especially (inner)urban dairy production is exposed to a challenging and highly land competitive environment but supported by tight linkages between dairy producers and consumers via the provisioning of fresh milk and socio-cultural services but at the cost of manure mismanagement and cow welfare.

A system approach to feed conversion efficiency of dairy production in an urbanizing environment

3.1 Introduction

Efficient resource utilization, such as high dairy feed conversion efficiency (FCE), is essential for sustainable agriculture (Romney et al., 1994). It is however challenged by two demographic drivers of change: population growth and spatial distribution shift from rural areas to urban ones, namely *urbanization* (Millennium Ecosystem Assessment, 2005). Urbanization induces a transition in the utilization of essential agricultural resources, mainly land. Land is affected by the physical fallout of urbanization, namely the conversion of arable lands and pasture into residential or industrial areas, and the fragmentation of the agricultural landscape (Satterthwaite et al., 2010). Urbanization also affects the demand for and supply of agricultural goods and services: on one hand, the demand is increased and diet preferences shift (Erler and Dittrich, 2017; Regmi and Dyck, 2001), which represents constraints but also market opportunities for producers. On the other hand, the number of people directly involved in agriculture, another essential agricultural resource, is decreasing (Satterthwaite et al., 2010). Urbanization however enhances market quality for agricultural producers, namely the access to inputs such as agrochemicals, compound feeds, veterinary services and modern plant and animal genetics (Duncan et al., 2013). By decreasing the availability of essentials agricultural resources but increasing access to production inputs and a larger output market, urbanization is thus seen as a main driver of agricultural intensification. At last, urbanization shapes food chains into unilateral resource flows from producers to consumers rather than as nutrient cycles. Through food, cities massively import nutrients and accumulate them, thereby becoming *nutrient sinks* (Drechsel et al., 2007), because the residues (waste and sewage) are not brought back to fields as organic (residue) fertilizers (Drechsel and Kunze, 2001; Prasad et al., 2019). Transition in resource utilization induced by an urbanizing environment thus challenges the efficiency of agricultural systems.

In the 1970s, Indian dairy production already faced challenges related to urbanization, whereby an increasing urban demand for dairy products was paralleled by poor rural-urban linkages and underdeveloped rural areas with a vast untapped dairy development potential (Cunningham, 2009; Duncan et al., 2013). Thus, India launched *Operation Flood*, a decades-long development program focusing on dairy production to scale up milk production, marketing and processing through dairy cooperatives and improve the livelihoods of numerous rural smallholders (Cunningham, 2009; Mascarenhas, 1988). Today’s Indian dairy sector is the largest in the world, dominated by smallholders, partly informal (Cunningham, 2009; FAOSTAT, 2019) and partly urban (Prasad et al., 2019), as testified by the presence of cattle in urban areas, despite a continuously urbanizing India (United Nations, 2019) and the constraints related to urban livestock production systems (Butler, 2012). The further development of Indian (peri-)urban dairy production is yet open and plural: tropical (peri-)urban livestock production systems show both dynamics of intensification and extensification (Roessler et al., 2016), and distinct production strategies to take advantage of and deal with the opportunities and constraints of urbanization (Daburon et al., 2017). They are, however, often characterized by poor resource utilization (Amadou et al., 2015; Diogo et al., 2010; Schlecht et al., 2019).

The increasing demand for milk in addition to its nature of high perishability and daily availability and the fact that (peri-)urban agricultural systems continue to use increasingly scarce and expensive spaces in West Africa and Asia (Graefe et al., 2019; Schlecht et al., 2019) led to the following research question: within the rural-urban interface (RUI) of an emerging Indian megacity, does urbanization lead to intensification or efficient resource utilization, measured as FCE, or both in dairy production? Our case study was dairy production in the RUI of Bengaluru, India, where feeding strategies, coverage of dairy cows' nutritional requirements, milk production and FCE were quantified at system-level during one year.

3.2 Materials and methods

3.2.1 Research area

Capital of the southern Indian state of Karnataka, Bengaluru is a megacity with over 10 million inhabitants, which grew at an unprecedented rate during the last decades (United Nations, 2018b; Verma et al., 2017). Its climate is hot semi-arid (average maximum temperature 29.5°C, average minimum temperature 18.5°C, 948 mm of annual rainfall (monthly average 2013-2017, weather station data, University of Agricultural Sciences Bangalore, GKVK campus) with a dry season (March-May) followed by monsoon (June-October) and winter (November-February). Along with Bengaluru's emergence as a megacity and multiple dairy development programs (Alderman, 1987; Nyholm et al., 1974), the number of dairy cattle increased: from around 25'000 cattle in 1972 (Nyholm et al., 1974) to 75'000 in 2012 (National Dairy Development Board, 2015). Two research transects were established following an urban to rural gradient, north and south-west of Bengaluru (Hoffmann et al., 2017). A survey stratification index based on build-up density of housing structures and distance to the city centre was assigned to each settlement within both transects as a proxy for urbanization level (urban, peri-urban and rural; Hoffmann et al., 2017).

3.2.2 Dairy production systems and selected units

Four dairy production systems (DPS) were characterized in Bengaluru's RUI, based on a cluster analysis of detailed farm data collected in individual surveys with 337 dairy producers from 32 settlements across both research transects (Table 3.1; Chapter 2). The characterization accounted for the degree of urbanization of a farm's neighbourhood, feeding management (self-cultivation of forage and access of cattle to pasture) and breeding management (genetic composition of the herd, type of cattle flow (buying as inflow; selling as outflow) within the herd). A stratified random selection was used to select 28 dairy production units (DPU) out of the 337, seven per DPS, with an overall balanced number of urban (4), peri-urban (8) and rural (16) DPU, distributed across 17 settlements (Figure 3.1). The head of the household managing the DPU was informed about the detailed protocol for nutrition monitoring and gave his or her oral consent before data collection started. Each of the 28 DPU was visited during one day in 6-week intervals for a total of eight visits between June 2017 and May 2018. The protocol for nutrition monitoring was adapted from Schlecht et al. (2019). Apart from weight quantification done on a voluntary basis (see below), all data were non-invasive and did not deviate from dairy producers' normal practices of animal management.

Table 3.1 Main characteristics of the four dairy production systems (DPS) within Bengaluru's rural-urban interface.

System	Spatial location	Breeding management		Feeding management		n LDH[1]
		Genotype	Cattle flow	Self-cultivated forages	Pasture	
DPS-1	Ubiquitous	Mixed	Closed	No	Yes	3.4 ± 2.0
DPS-2	Rural	Exotic	Closed	Yes	Yes	2.7 ± 0.9
DPS-3	Rural	Mixed	Balanced	Yes	Yes	3.1 ± 1.3
DPS-4	Rural	Exotic	Negative	Yes	No	3.1 ± 1.9

[1] n LDH: number of lactating and dry cows plus mature heifers (mean ± standard deviation).

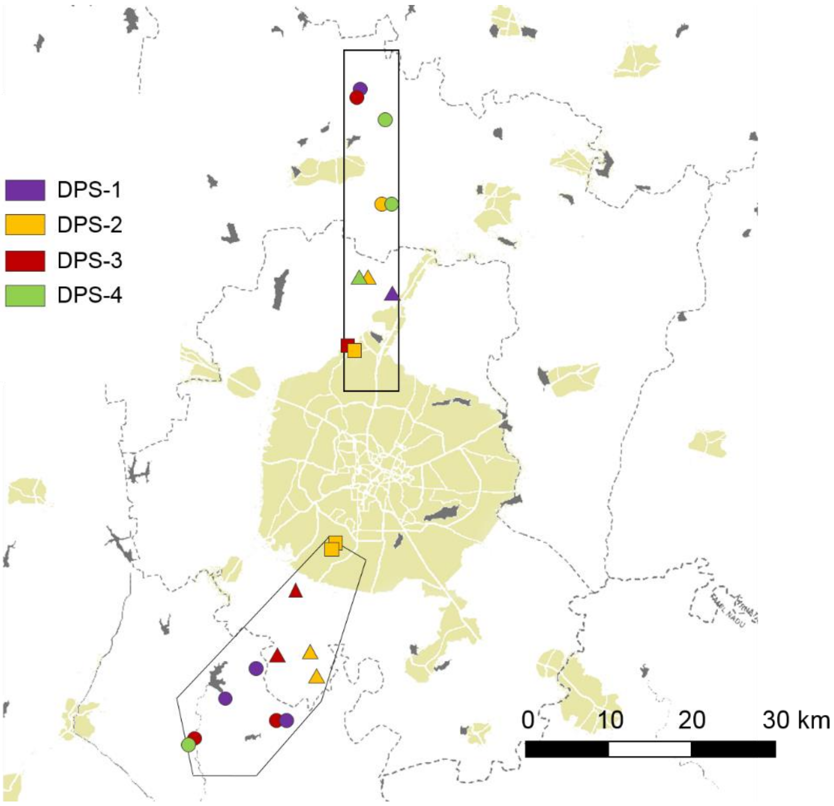

Figure 3.1 Location of the 17 settlements in which dairy production units (DPU) were selected for nutrition monitoring. Irrespective of colour, a square marks an urban settlement, a triangle an peri-urban settlement and a circle a rural settlement. Irrespective of shape, each colour marks one dairy production system (DPS). The two research transects are delimited in black.

3.2.3 Data collection

General data. Twenty data loggers (Voltcraft DL-101TH) were installed amongst the 28 DPU to record temperature and humidity at one-hour intervals (345 days of record from June 2017 to May 2018). The daily temperature-humidity index (THI; National Research Council, 1971) was calculated as the 24-hour average of hourly THI:

$$\mathrm{THI_{Hour}} = (1.8 \times \mathrm{T} + 32) - (0.55 - 0.0055 \times \mathrm{RH}) \times (1.8 \times \mathrm{T} - 26) \qquad \text{Eq. 1}$$

where T is temperature in degree Celsius and RH is relative humidity in percent.

At the first visit, all dairy cattle were photographed, characterized (breed, physiological status, lactation number, last calving; n = 176) and classified into three genotype categories: *exotic* including purebred Holstein Friesian and Jersey (55%), *Cross-I* including exotic first-generation crossbreeds (18%), and *Cross-II* including *exotic x native* first-generation crossbreeds and all multi-generation crossbreeds (27%). The information was amended at successive visits, with each new dairy cattle characterized likewise. Lactating (L) or dry (D) cows plus mature heifers (H; pregnant or at least already inseminated once) were considered as the productive dairy herd (LDH; n = 107). When relevant, the physiological status of LDH was characterized with 1 = pregnant or (potentially) pregnant in the case of heifers, and 0 = not pregnant, resulting into four categories: L0 (lactating cow, not pregnant), L1 (lactating cow, pregnant), D1 (dry cow, pregnant) and H1 ((potentially) pregnant heifer).

Quantitative and qualitative determination of on-farm feed intake. At each visit, at best each meal or otherwise a representative number of meals of each LDH were quantified according to the 24-hour feeding pattern. Each offered feedstuff or mix (usually concentrate feed, sometimes green forages) was characterized (type, self-cultivated or bought) and weighed (Hanging scale PCE-HS 50N: 0.20-50.00 kg, accuracy ± 0.08 kg). Afterwards, group or individual feed intake was quantified by re-weighing refusals wherever relevant and possible. In some cases, refusals were mixed with excreta due to a lack of proper feeding throughs or accumulated from more than one meal, which prevented their quantification. Therefore, calculated daily feed intake values exceeding physiological dry matter (DM) intake limits of an individual animal (Ulbrich et al., 2004) were excluded from the analysis, resulting in 641 individual feeding records at LDH-level. Of individual feedstuffs and mixes that were fed at each farm and visit, 321 representative samples were collected. Their weight before and after air and oven drying (at 80°C for 24 hours; USB, Forced Convection Oven 411-500420) was determined (Kern PCB 10000-1, 0.0-10.0 kg ± 0.1 kg; Denver Instruments TP-124, 0.1 mg – 210 g, ± 0.0001 g); dry samples were ground to 0.5 mm particle size (mixer grinder) and analysed for concentrations of DM (AOAC International, 2012; Method 934.01) and crude protein (CP; AOAC International, 2012; Method 955.01 (Kjeldahl); Gerhardt protein analyser VAPODEST450). In-vitro digestible organic matter (DOM) content was determined according to Menke et al. (1979). To assess the feedstuffs' metabolizable energy (ME) content, a DOM to ME regression ($R^2 = 0.9261$) was established based on 93 selected records from Close and Menke (1986) and Feedipedia.

Pasture intake and daily locomotion. The time cattle spent pasturing per day was asked from the dairy producers. Manual observation of behaviour at pasture over 24-hours was done once in five DPU (two urban, one peri-urban, two rural) for one to two LDH (n = 9 *animal x day observation* sets) to assess the time spent grazing as a fraction of the total time spent on pasture: this was, on average, 42% of pasture time in urban areas and 77% in peri-urban and rural areas. Daily feed intake on pasture was calculated with an intake rate of 8 g DM per kg metabolic weight (MW = body weight scaled to the power of 0.75; Ayantunde et al., 2002). The average quality of 32 samples of non-cultivated grasses (collected by dairy producers for on-farm feeding from public spaces) was used to calculate nutrient intake from pasture in peri-urban and rural settlements. A weighted average value (50:50) of the quality of 32 samples of non-cultivated grasses plus 3 samples of vegetable and fruit mixes was used to calculate nutrient intake from pasture in urban settlements, where cows had additionally access to household or market organic wastes dumped in the streets. On average 15% of the daily time on pasture was spent on walking. The ME requirement for locomotion was set at 2.01 kJ per kg body weight (BW) and km (Menke and Huss, 1987) with a standard average walking speed of 2.5 km per hour.

Milk offtake and quality. As direct consumption of milk by the calf was sometimes allowed (24% of all milking records: from suckling to stimulate milk let-down to complete feeding of the calf) but impossible to quantify, milk data per cow is referred to as milk offtake (MO). Individual MO was quantified twice a day if possible. Else, individual MO in the morning was estimated based on the recorded quantity of milk delivered to the dairy cooperative plus the milk quantities used for family consumption, direct marketing and calf feeding, and the afternoon share of production per L. A California mastitis test was done during afternoon milking for each individual L. Degree of mastitis was categorized according to the number and degree of infected teats with A = no mastitis, B = traces, C = mild mastitis and D = severe mastitis. An individual milk sample was analysed for fat and protein content (Lactoscan Milk Analyzer, Softrosys Technologies, Bengaluru, India) to assess the relevance of metabolic disorders, with a fat-to-protein ratio below 1.0 indicating risk of acidosis and above 1.5 risk of ketosis (Eicher, 2004). Daily energy corrected milk (ECM; 4% fat and 3.3% protein; Sjaunja et al., 1990) was calculated as follows:

$$\mathrm{ECM} = \mathrm{kg\ MO} \times (0.25 + 0.122 \times \mathrm{Fat} + 0.077 \times \mathrm{Protein}) \qquad \text{Eq. 2}$$

where MO is milk offtake in kg per day, Fat is fat percentage of the milk and Protein is protein percentage of the milk.

The energy requirement for the synthesis of milk was set at 5.3 MJ ME per kg ECM and the protein requirement at 85 g CP per kg ECM (Ulbrich et al., 2004).

Maintenance, growth and gravidity requirements. A standard value of 480 kJ ME and 3.7 g CP per kg MW and day was used to calculate the daily maintenance requirement of ME and CP (Ulbrich et al., 2004). To quantify growth of individual dairy animals, including foetal growth, a heart girth (HG) to BW regression (Vanvanhossou et al., 2018) was established based on 569 weight records (Weighing Set EziWeigh 5, load bars MP600) collected in November 2017 across the whole RUI and cattle of all categories of sex, age, genotype and physiological status:

$$\mathrm{BW} = -3.867 + 2.98 \times \log_{10}(\mathrm{HG}) \qquad \text{Eq. 3}$$

where BW is body weight in kg and HG is heart girth in cm, with a correlation coefficient of the equation of $R^2 = 0.9846$ (Grund, 2018).

Growth was calculated as the daily body weight gain or loss (Δ BW g per day) as estimated from HG measurements at 6-week intervals. ME and CP requirements were set at 34.0 MJ ME and 380 g CP per kg Δ BW in the case of weight gain (Ulbrich et al., 2004), whereas no requirements (and also no freed energy and protein) were factored in case of weight losses.

3.2.4 Statistical analyses

Feed intake and feed conversion efficiency. Intake of DM, CP and ME on-farm and on pasture were calculated per kilogram of MW. Values were compared between DPS, genotypes and physiological status of LDH using Kruskal-Wallis test (Holm correction for pairwise comparison) because normal distribution and homogeneity of variances were not achieved (Shapiro-Wilk test, $P < 0.05$). Once total intake and ME and CP requirements for maintenance, growth, locomotion and milk production were calculated, categorical supply levels of ME and CP were defined as the ratio of intake to requirement and classified as adequate supply (ratio = 0.8 - 1.2), mild deficit (0.5 - < 0.8), severe deficit (< 0.5), mild surplus (> 1.2 – 1.5) and substantial surplus (> 1.5; Wassie et al., 2019). Kruskal-Wallis test was used to assess differences in numerical ME and CP supply ratios between DPS, genotypes and physiological status, whereas chi-squared test was used to determine differences in the frequency of ME and CP supply levels between DPS, genotypes and physiological status. As DPU within each DPS had similar feeding strategies, no DPU effect was considered in the analyses of intake and FCE. Significance was declared at $P < 0.05$ for all analyses.

Milk offtake. MO was compared between DPS using Kruskal-Wallis test. A stepwise regression was used to investigate the relations between MO, corrected to 100 kg BW (cMO; n = 332) and dairy production variables. Dairy production variables considered as fixed effects were DPS, days-in-milk (DIM, numerical, intervall: 3-559), genotype category (categorical, 3 levels), total daily DM intake (DMI), ME and CP coverage ratio (ME.cov and CP.cov; continuous), metabolic disorders based on fat-to-protein ratio of the milk (categorical, 3 levels), pregnancy (Preg; yes, no), calf directly suckling milk (yes, no), mastitis (categorical, 4 levels), urbanization degree (urban, peri-urban, rural), round (R; categorical, 8 levels) and THI (continuous). DPU (28) and cow (75) were considered as random effects. Dairy producers often did not known the lactation number of cows they bought which resulted in a lot of missing data. As a stepwise regression requires the exclusion of all incomplete observations, lactation number was not considered in the final stepwise regression after prelimary stepwise regressions did not find it a significant factor, to preserve a high number of observations.

3.3 Results

3.3.1 Type of feedstuffs and seasonal contribution

On-farm, dairy producers usually fed one to two green or dry feedstuffs per day to their LDH cattle starting from after the morning milking until late in the night, with 2.7 ± 3.3 hours of pasture in-between (overall LDH average). The most important self-cultivated or bought green forages (DM content from 10 to 76%; Table 3.2) were African tall maize (*Zea mays*) and hybrid Napier grass (*Pennisetum glaucum* × *P. purpureum)*. Most dairy producers were also collecting a wide range of wild (non-cultivated) grasses from green spaces and, in urban areas, also from the surroundings of lakes. Green forages were consistently the main feedstuff fed, although their contribution decreased during winter and the dry season in comparison to the monsoon time (Figure 3.2). Urban dairy producers (DPS-2) additionally relied on organic wastes from markets (field bean pods, cabbage, banana peels, sugarcane bagasse, amongst others) that they were getting at a low price or for free (20% contribution over the year, inexistent in other DPS).

Table 3.2 Mean concentration of dry matter (DM), crude protein (CP), metabolizable energy (ME), and digestible organic matter (DOM) per type of feedstuff (n feed samples analysed = 321).

Type of feedstuff	n	DM (% in FM)	CP (g/kg DM)	ME (MJ/kg DM)	DOM (% in DM)
Green forages	191	27	76	8	59
Dry forages	37	90	44	7	54
Crop residues, organic wastes	12	21	85	10	68
Concentrate feed	81	89	167	11	77
Pasture biomass	32[1]	27	88	8	58
Urban pasture biomass	32:3[2]	19	92	10	68

FM: fresh matter.

[1] average quality of 32 samples of green forages (non-cultivated grasses collected by dairy producers for on-farm feeding from public spaces).

[2] weighted average value (50:50) of pasture biomass (32 samples) and organic wastes (3 samples of vegetable and fruit mixes.

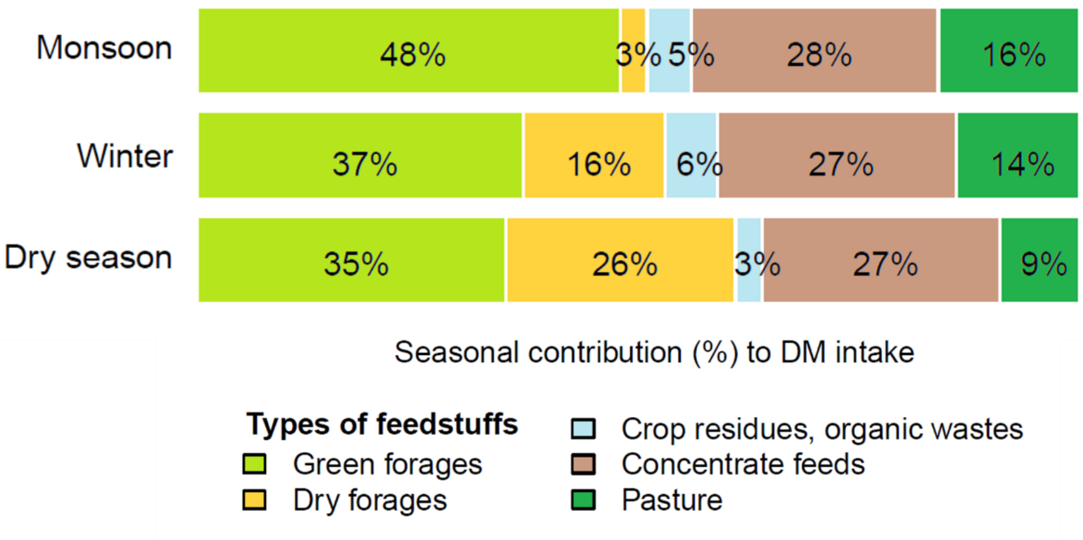

Figure 3.2 Seasonal contribution (%) to total daily dry matter (DM) intake of lactating and dry cows plus mature heifers per type of feedstuff and season in 28 dairy production units located within the rural-urban interface of Bengaluru, India.

Figure 3.3 Example of organic wastes collected on markets by urban dairy producers to fed their cattle (right) and a cow feeding on organic wastes in the shed (left).

Dry forage (DM content from 84 to 92%; Table 3.2) was commonly straw of finger millet (*Eleusine coracanal*, known as ragi) and occasionally dried maize (straw without cobs). Dry forages were mostly fed during the winter and dry season when green forages' availability was reduced because of low water availability (Figure 3.2). There was a large range of concentrate feed available in Bengaluru's RUI: wheat flour, with or without bran, corn flour, dairy pellets, chickpea husks (*Cicer arietinum*, known as Bengal gram) and groundnut cake, to which dairy producers added raw salt or a mineral mixture. Some concentrate feed were obtained through the dairy cooperative at a subsidized price, others were bought from merchants. Out of the 28 DPU, 27 fed concentrate feed daily either as single element or in a mix: usually all lactating and dry cows received a similar concentrate share twice a day, while mature heifers received less or different components or both. Overall, concentrate feed contributed to 27-28% of the daily DMI (DMI) on-farm, irrespective of the season (Figure 3.2). Out of the 28 DPU, 19 sent their LDH cattle to pasture, on a daily (7), seasonal (8) or irregular (4) basis. On average, the cattle stayed on pasture for 5.9 ± 2.3 hours (average of only LDH sent to pasture), actively grazing during 4.1 ± 1.7 hours (DMI at pasture from 0.6 to 7.1 kg DM LDH^{-1} day^{-1}). The distance walked when pasturing averaged 2.2 ± 0.9 km day^{-1}.

3.3.2 Feeding intensity

The feeding management of each DPS was clearly reflected in the daily DM, CP and ME intake per kg MW: dairy producers from DPS-1 did not cultivated their own forage but relied on pasturing, grasses collected from public green spaces and market wastes while rarely purchasing forages without accounting for the heavier BW of their cattle (421 ± 58 kg BW; $P < 0.05$; Table 3.3). This extensive feeding management resulted in the lowest DMI on-farm amongst the four DPS (94 ± 56 g kg^{-1} MW; $P < 0.05$). CP (9 ± 7 g kg^{-1} MW; $P < 0.05$) and ME (863 ± 484 kJ kg^{-1} MW; $P < 0.05$) intake on-farm were similarly the lowest. Pasture contributed 22% of total daily DMI of DPS-1 cattle but did not compensate for the low intake on-farm. Therefore, overall DM (113 ± 48 g kg^{-1} MW), CP (11 ± 6 g kg^{-1} MW) and ME (1015 ± 415 kJ kg^{-1} MW) intake remained the lowest amongst the four DPS ($P < 0.05$). Dairy producers from DPS-2 and DPS-3 relied on both self-cultivated forage and pasture, achieving similar intermediate overall DM, CP and ME intake; however, DPS-2 producers sent their cattle longer to pasture (23% of daily DMI from pasture) than DPS-3 producers (12%; $P < 0.05$) to compensate for a lower intake on-farm. Dairy producers from DPS-4 pursued an intensive feeding management by feeding their cattle almost exclusively on-farm (2% of daily DMI from pasture) reaching the highest DM, CP and ME intake on-farm ($P < 0.05$) and overall (173 ± 45 g DM kg^{-1} MW, 17 ± 6 g CP kg^{-1} MW and 1547 ± 440 kJ ME kg^{-1} MW; $P < 0.05$), even when accounting for pasture intake in the other DPS. Total DM offer per day showed the same intake gradient, ranging from a low 10.52 kg DM LDH^{-1} day^{-1} in DPS-1 to a high 15.29 kg DM LDH^{-1} day^{-1} in DPS-4 ($P < 0.05$; Table 3.4).

Irrespective of DPS, BW differed according to genotype: exotic cattle were the heaviest (407 ± 71 kg BW; $P < 0.05$), while first- and multi-generation crossbreeds weighted less (Cross-I = 376 ± 57 kg BW; Cross-II = 373 ± 60 kg BW; Table 3.5). Moreover, all exotic cattle received an extra supply of ME on-farm ($P < 0.05$) and pasture contributed less (12%) to their DMI as compared to Cross-II (19%; $P < 0.05$). Irrespective of DPS, DMI from pasture was independent of physiological status (averaging 14% of total daily DMI) but daily DM, CP and ME intake on-farm differed: non-pregnant lactating cows consumed more feed DM than pregnant lactating cows ($P < 0.05$) resulting in higher overall ME intake ($P < 0.05$ for L0 *versus* L1) but not higher daily CP intake. Pregnant dry cows had similar DM, CP and ME intake than pregnant and non-pregnant lactating cows. Despite being the lightest animals (354 ± 81 kg BW; $P < 0.05$) amongst LDH, mature heifers had systematically lower daily DM, CP and ME intakes per MW than non-pregnant lactating cows ($P < 0.05$), yet their intake was in the range of pregnant lactating and dry cows.

Table 3.3 Mean body weight, daily dry matter (DM), crude protein (CP) and metabolizable energy (ME) intake of lactating and dry cows plus mature heifers on-farm and overall (intake on-farm plus pasture) relative to metabolic weight (MW), and pasture contribution to daily intake (% DM) in the four dairy production system (DPS) of Bengaluru's rural-urban interface (total individual nutrition records collected from 28 dairy production units over one year = 641).

DPS	n	Body weight (kg)	On-farm feed intake			Overall intake			Pasture share (% DM)
			DM (g kg^{-1} MW)	CP (g kg^{-1} MW)	ME (kJ kg^{-1} MW)	DM (g kg^{-1} MW)	CP (g kg^{-1} MW)	ME (kJ kg^{-1} MW)	
DPS-1	140	421^{a}	94^{a}	9^{a}	863^{a}	113^{a}	11^{a}	1015^{a}	22^{a}
DPS-2	144	349^{b}	114^{b}	11^{b}	1026^{b}	143^{b}	14^{b}	1258^{b}	23^{a}
DPS-3	199	400^{ac}	133^{c}	13^{b}	1168^{c}	149^{b}	14^{b}	1296^{b}	12^{b}
DPS-4	158	401^{c}	170^{d}	17^{c}	1525^{d}	173^{c}	17^{c}	1547^{c}	2^{c}
SEM		*2.7*	*2.3*	*0.2*	*20.5*	*1.9*	*0.2*	*17.6*	*0.7*

Values within a column with different superscript letters differ significantly at $P < 0.05$.

Table 3.4 Mean daily dry matter intake (DMI), metabolizable energy (ME) and crude protein (CP) coverage ratio (intake over requirements) per dairy cattle, corrected milk offtake (cMO; kg Energy-corrected milk (ECM) per 100 kg body weight (BW) and per day) and feed conversion efficiency (FCE; kg of ECM per kg of DM intake) by dairy production system (DPS) in Bengaluru's rural-urban interface.

DPS	n	DMI (kg DM cow^{-1} day^{-1})	n	ME coverage ratio	n	CP coverage ratio	n	cMO (kg ECM 100 kg^{-1} BW day^{-1})	n	FCE (kg DMI kg^{-1} ECM)
DPS-1	141	10.52^{a}	108	1.05^{a}	105	0.95^{a}	105	2.24^{a}	105	1.00^{a}
DPS-2	146	11.59^{b}	110	1.32^{b}	102	1.19^{b}	101	2.34^{a}	101	0.71^{b}
DPS-3	202	13.21^{c}	151	1.34^{b}	143	1.24^{b}	129	2.51^{ab}	129	0.77^{b}
DPS-4	161	15.29^{d}	115	1.42^{b}	108	1.31^{b}	116	2.7^{8b}	116	0.72^{b}
SEM		*0.2*		*0.0*		*0.0*		*0.0*		*0.0*

Values within a column with different subscript letters differ significantly at $P < 0.05$.

Table 3.5 Mean daily dry matter (DM), crude protein (CP) and metabolizable energy (ME) intake on-farm and in total (intake on-farm plus pasture) per dairy cattle relative to metabolic weight (MW), and pasture share (% DM), by genotype and physiological status in Bengaluru's rural-urban interface (total individual nutrition records collected from 28 dairy production units over one year; n = 641 for genotype and n = 616 for physiological status).

Variable	n	Body weight (kg)	On-farm intake			Total intake			Pasture share (% DM)
			DM (g kg^{-1} MW)	CP (g kg^{-1} MW)	ME (kJ kg^{-1} MW)	DM (g kg^{-1} MW)	CP (g kg^{-1} MW)	ME (kJ kg^{-1} MW)	
Genotype									
Exotic	380	407^{a}	134	13^{a}	1204^{a}	149	15^{a}	1322	12^{a}
Cross-I	83	376^{b}	122	11^{b}	1088^{ab}	135	13^{b}	1194	13^{ab}
Cross-II	178	373^{b}	123	12^{ab}	1091^{b}	144	14^{ab}	1259	19^{b}
SEM		*2.7*	*2.3*	*0.2*	*20.5*	*1.9*	*0.2*	*17.6*	*0.7*
Physiological status									
Lactating	297	392^{A}	139^{A}	13^{A}	1253^{A}	155^{A}	15^{A}	1379^{A}	13
Lactating, pregnant	161	398^{A}	124^{B}	13^{AB}	1122^{B}	143^{B}	15^{AB}	1274^{B}	16
Dry, pregnant	88	416^{A}	127^{AB}	12^{AB}	1114^{AB}	144^{A}	14^{AB}	1248^{AB}	15
Mature heifer	70	354^{B}	112^{B}	10^{C}	954^{B}	125^{B}	12^{B}	1057^{C}	14
SEM		*2.7*	*2.3*	*0.2*	*20.5*	*1.9*	*0.2*	*17.6*	*0.7*

Values within a column with different lowercase (genotype) or capital (physiological status) subscript letters differ significantly at $P < 0.05$.

3.3.3 Energy and protein coverage

Nutrient requirements. Weight differences in LDH kept by the four DPS were reflected in low daily maintenance requirements for ME and CP in DPS-2, intermediate requirements in DPS-3 and DPS-4, and high requirements in DPS-1. Daily weight gain (Δ BW g day^{-1}) did not differ between DPS (overall average: 552 ± 336 g day^{-1}, excluding cattle that just maintained or lost weight). Daily ME and CP requirements for milk production differed between DPS due to differences in daily MO per cow ($P < 0.5$, see below) and represented around half of the total daily requirements. Daily ME requirements for locomotion also differed between DPS ($P < 0.05$), reflecting the differences in daily pasturing time. When comparing the ME requirements for locomotion of only those cattle sent grazing, there was however no difference despite variation in daily pasturing time. Overall, daily ME requirement per productive dairy animal was lowest in DPS-2 (76 ± 26 MJ ME day^{-1}), intermediate in DPS-3 (82 ± 38 MJ ME day^{-1}), and highest in DPS-1 (89 ± 32 MJ ME day^{-1}) plus DPS-4 (90 ± 36 MJ ME day^{-1}; DPS-2 *versus* DPS-1 and DPS-4 $P < 0.05$). Likewise, overall daily CP requirements per productive dairy animal were lowest in DPS-2 (849 ± 396 g CP day^{-1}), intermediate in DPS-3 (924 ± 536 g CP day^{-1}), and highest in DPS-1 (1003 ± 473 g CP day^{-1}) and DPS-4 (1065 ± 542 g CP day^{-1}; $P <0.05$ for DPS-2 *versus* DPS-1, DPS-4).

Metabolizable energy supply. On average, cattle in DPS-1 were adequately supplied with ME (1.05 ± 0.47; Table 3.4) but there were strong disparities: 37% of LDH cattle were undersupplied and 35% oversupplied while only 28% were in truth adequately supplied (Figure 3.4). In comparison, the average ME coverage ratio characterized a mild ME oversupply in the three other DPS ($P < 0.05$ for DPS-1 *versus* DPS-2, DPS-3, DPS-4): barely any cattle were undersupplied but rather more than 50% of the cattle were systematically oversupplied with ME, especially in DPS-4 where cattle were intensively stall-fed. Overall, ME undersupply was not an issue in DSP-2, DPS-3 and DPS-4, while ME supply of LDH cattle in DPS-1 showed discrepancies in individual coverage of ME requirements but no systematic severe deficit (see Table 3.7 for absolute number LDH observations per ME supply level).

Irrespective of DPS, the ME supply ratio was also affected by genotype, with first-generation crosses adequately supplied (average ratio: 1.16 ± 0.47) and exotic cattle mildly oversupplied (1.33 ± 0.45; $P < 0.05$), while ME supply to Cross-II cattle was intermediate (Table 3.6). Irrespective of DPS, discrepancies in the ME supply ratio were strongest with respect to the physiological status of the cattle: dry pregnant cows (1.74 ± 0.50) and mature heifers (1.55 ± 0.52) were substantially oversupplied while lactating cows experienced an adequate to mild ME oversupply, irrespective of pregnancy (1.19 ± 0.40) or not (1.21 ± 0.39; $P < 0.05$ for L0, L1 *versus* D1, H1; Figure 3.5 and Table 3.6).

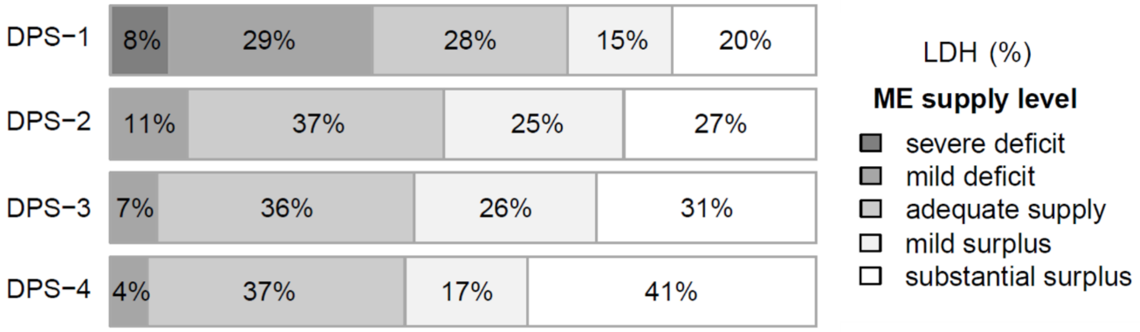

Figure 3.4 Share of lactating and dry cows plus mature heifers (LDH) per metabolizable energy (ME) supply level (ratio between individual metabolizable energy intake and requirement for maintenance, growth including pregnancy, milk production and locomotion) for the four dairy production systems (DPS) of Bengaluru's rural-urban interface; adequate supply equals a ratio between 0.8-1.2, mild deficit between 0.5 - < 0.8, severe deficit < 0.5, mild surplus between > 1.2 – 1.5, and severe surplus > 1.5.

Table 3.6 Mean metabolizable energy (ME) and crude protein (CP) coverage ratio (intake over requirements) per dairy cattle by genotype and physiological status in Bengaluru's rural-urban interface (total individual nutrition records collected from 28 dairy production units and over one year).

Variable	n	ME coverage ratio	n	CP coverage ratio
Genotype				
Exotic	289	1.33^{a}	278	1.24^{a}
Cross-I	63	1.16^{b}	58	0.99^{b}
Cross-II	132	1.28^{ab}	122	1.14^{ab}
SEM		*0.0*		*0.0*
Physiological status				
Lactating	248	1.21^{A}	250	1.06^{A}
Lactating, pregnant	112	1.19^{A}	113	1.16^{A}
Dry, pregnant	54	1.74^{B}	35	1.71^{B}
Mature heifer	52	1.55^{B}	42	1.65^{B}
SEM		*0.0*		*0.0*

Values within a column with different lowercase (genotype) or capital (physiological status) subscript letters differ significantly at $P < 0.05$.

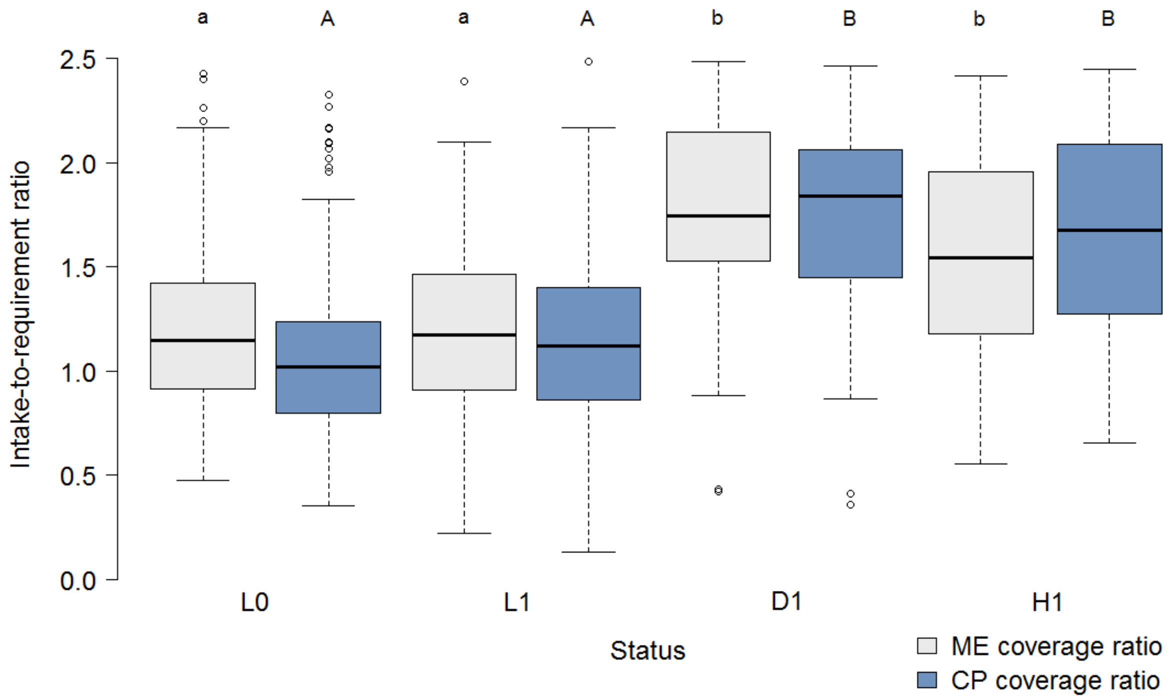

Figure 3.5 Intake-to-requirements ratio of metabolizable energy (ME) and crude protein (CP) for heifers and cows of different physiological status (L0: lactating, not pregnant cow; L1: lactating, pregnant cow; D1: dry, pregnant cow; H1: mature heifer). The black line shows the median value for each group, the box the interquartile range, the whiskers the first and third quartiles and the circles are outlier values. Boxplots with different lowercase (ME coverage ratio) or capital (CP coverage ratio) superscript letters significantly differ at $P < 0.05$.

Crude protein supply. Paralleling the findings for ME coverage, on average, cattle in DPS-1 were adequately supplied with CP (ratio: 0.95 ± 0.49; Table 3.4) but there were strong disparities with 44% of LDH cattle undersupplied and 25% oversupplied, while only 31% were adequately supplied (Table 3.4). Again, the average CP coverage ratio characterized a higher CP supply in the three other DPS (adequate to mild oversupply; $P < 0.05$ for DPS-1 *versus* DPS-2, DPS-3, DPS-4). CP coverage ratios were however lower than those of ME, with a similar share of adequately supplied and oversupplied cattle in DPS-2 and DPS-3. DPS-4, however, oversupplied more than 50% of its cattle with CP as a result of its intensive feeding management. As for ME supply, CP undersupply was no crucial issue in DSP-2, DPS-3 and DPS-4 but was more common in DPS-1. Because of the better intake to requirement ratio, CP supply was however more adequate than ME supply in general (see Table 3.7 for absolute number LDH observations per CP supply level).

Irrespective of DPS and still paralleling the findings for ME coverage, the CP supply ratio was also affected by genotype, with Cross-I adequately supplied (ratio: 0.99 ± 0.53) and exotic cattle mildly oversupplied (1.24 ± 0.47; $P < 0.05$), while CP supply of Cross-II was intermediate (Table 3.6). Irrespective of DPS, discrepancies in the CP supply ratio were again strongest with respect to the physiological status of the cattle: dry pregnant cows (1.71 ± 0.54) and mature heifers (1.65 ± 0.54) were substantially oversupplied while lactating cows experienced an adequate CP supply, irrespective of being pregnant (1.16 ± 0.47) or not (1.06 ± 0.37; $P < 0.05$ for L0 and L1 *versus* D1 and H1; Figure 3.5 and Table 3.6).

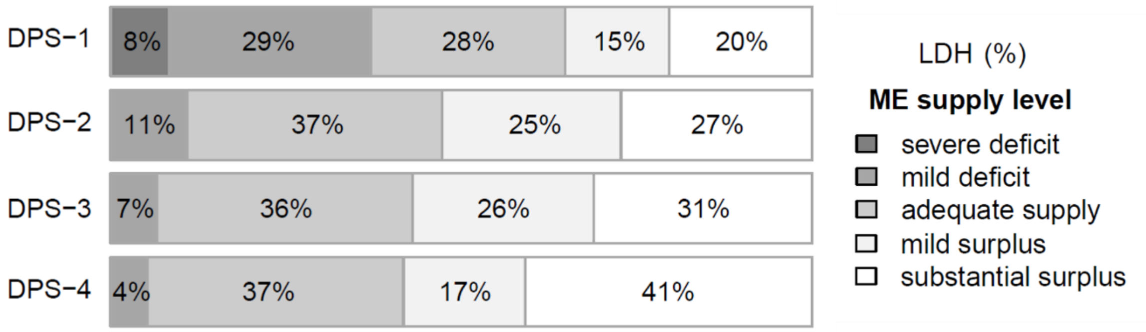

Figure 3.6 Share of lactating and dry cows plus mature heifers (LDH) per crude protein (CP) supply level (ratio between individual crude protein intake and requirements for maintenance, growth, including foetal growth, and milk production) for the four dairy production systems (DPS) of Bengaluru's rural-urban interface; adequate supply equals a ratio between 0.8-1.2, mild deficit between 0.5 - < 0.8, severe deficit < 0.5, mild surplus between > 1.2 – 1.5 and severe surplus > 1.5; * = 1%.

3.3.4 Milk offtake and feed conversion efficiency

Lactation number differed according to DPS, being lowest in DPS-4 (2.4 ± 1.5) and highest in DPS-3 (3.2 ± 2.2; $P < 0.05$), while intermediate in DPS-1 (3.3 ± 2.6) and DPS-2 (2.6 ± 1.5; Table 3.7). Daily MO per cow differed according to DPS, being lowest in DPS-2 with 8.19 ± 3.01 kg ECM cow^{-1} day^{-1} and highest in DPS-3 (10.23 ± 3.96 kg ECM cow^{-1} day^{-1}) and DPS-4 (10.88 ± 4.47 kg ECM cow^{-1} day^{-1}; $P < 0.05$ for DPS-2 *versus* DPS-3, DPS-4), while MO in DPS-1 was intermediate (9.49 ± 4.17 kg ECM cow^{-1} day^{-1}; Figure 3.7). When corrected for the animals' BW, the differences between DPS-1, DPS-2 and DPS-3 flattened out while DPS-4 reached the highest cMO with 2.78 ± 1.12 kg ECM 100 kg^{-1} BW day^{-1} ($P < 0.05$ for DPS-4 *versus* DPS-1, DPS-2; Table 3.4). In terms of FCE (kg ECM per kg DMI) however, DPS-1 performed best, reaching 1.00 ± 0.48 kg ECM kg^{-1} DM ($P < 0.05$) while FCE was less variable but low in DPS-2 (0.71 ± 0.23), DPS-3 (0.77 ± 0.28) and DPS-4 (0.72 ± 0.32; Figure 3.7; Table 3.4). Out of 383 milk samples, 14% pointes to risk of acidosis and 30% to risk of ketosis (Table 3.7).

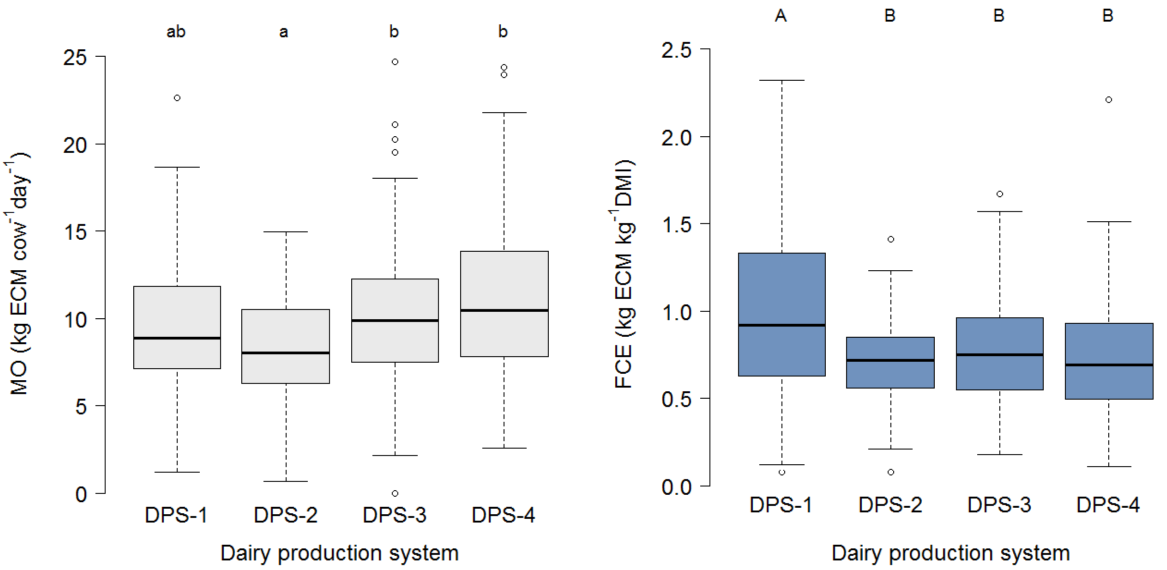

Figure 3.7 Daily milk offtake (MO; kg Energy-Corrected-Milk (ECM) per cow and day; left) and feed conversion efficiency (FCE; kg ECM per kg dry matter intake (DMI); right) for the four dairy production systems (DPS) of Bengaluru's rural-urban interface. Please note the different scaling of the y-axes. The black line shows the median value for each group, the box the interquartile range, the whiskers the first and third quartiles and the circles are outlier values. Boxplots with different lowercase (MO) or capital (FCE) superscript letters differ significantly at $P < 0.05$ ($n= 451$).

The stepwise regression retained seven production variables as fixed effects for cMO and cow as random effect (Table 3.8). Random effect of DPU was not significant, which underlined the consistency of the selected DPU, but DPS was, which indicated that some variation in cMO was not captured by the twelve dairy production variables at DPU-level and cow-level. In line with previous MO results, DPS-4 had a positive effect on cMO, while DPS-2 and DPS-3 performed worse than DPS-1. Additional relevant factors for cMO were: days-in milk (DIM; negative correlation); genotype (GEN) with Cross-I having a positive effect while Cross-II had a negative one; DM intake per day (DMI; positive correlation) and ME coverage ratio (ME.cov; negative correlation) but not CP coverage ratio nor metabolic disorders; pregnancy (Preg) decreased cMO but calf directly sucking milk and mastitis had no effect, despite their prevalence(Table 3.7); cMO showed a seasonal pattern as round (R) had an effect with cMO decreasing during round 4 to 8 (winter and dry season) but not because of THI, despite THI significantly differing across seasons ($P < 0.05$; Table 3.9); Finally, urbanization level was not significant, indicating that no variation in cMO due to spatially explicit production variables was missed. The stepwise regression is hence expressed as:

$$cMO_{ijklmnop} = DPS_i + DIM_j + GEN_k + DMI_l + ME.cov_m + Preg_n + R_o + cow_p + e_{ijklmnop}$$

Table 3.7 Absolute number of LDH observations per metabolizable energy (ME; n = 481) and crude protein (CP; n = 458) supply level, mean lactation number, absolute number of LD observations per lactation number (n = 421), mean fat-to-protein ratio of milk, absolute number of L observations per metabolic disorders levels (n = 383) and mastitis level (453) per dairy production system (DPS) and overall.

Variables	DPS-1	DPS-2	DPS-3	DPS-4	Overall
ME supply level					
Severe deficit	9*	0	0	0	9
Mild deficit	31*	12	10	6*	59
Adequate supply	30	40	55	40	167
Mild surplus	16	28	39	20	103
Substantial surplus	22	30	47	47*	146
CP supply level					
Severe deficit	24*	1	0*	0*	25
Mild deficit	22	17	19	18	76
Adequate supply	32	40	65	36	173
Mild surplus	14	23	23	20	80
Substantial surplus	13*	21	36	34	106
Lactation number	2.6 ± 1.5^{ab}	3.3 ± 2.6^{ab}	3.2 ± 2.2^{a}	2.4 ± 1.5^{b}	-
Lactation number					
1st lactation	33	30	14	43	120
2nd lactation	23	36	22	15	96
3rd lactation	8	9	42	38	97
4th lactation	1	20	15	4	40
5th lactation	8	13	4	4	29
6-11th lactation	24	3	6	6	39
Fat-to-protein ratio of milk	1.2 ± 0.3^{a}	1.3 ± 0.3^{b}	1.3 ± 0.3^{b}	1.4 ± 0.3^{c}	-
Metabolic disorders					
Normal	60	67	86	72	213
Acidosis	25	11	12	5	53
Ketosis	21	24	32	40	117
Mastitis					
A = no mastitis	60	56	78	70	264
B = traces	30	21	25	18	94
C = mild mastitis	13	18	27	20	78
D = severe mastitis	3	6	2	6	17

*Frequency of observation within a row differs significantly from overall frequency ($P < 0.05$).

Values within a row with different subscript letters differ significantly at $P < 0.05$.

Table 3.8 Summary of the outcomes from the stepwise regression with cow as random effect and effect of additional fixed dairy production variables (n observation = 332).

Variable	Level	n	Fixed effect	Significance
Intercept	-	-	2.87	-
DPS	DPS-1	78	-	**
	DPS-2	75	-0.26	
	DPS-3	94	-0.25	
	DPS-4	85	0.32	
DIM	-	332	2 x 10^{-3}	***
Genotype	Exotic	197	-	*
	Cross-I	45	0.33	
	Cross-II	90	-0.22	
DM intake		332	0.13	***
ME coverage ratio	-	332	-1.24	***
Pregnancy	No	239	-	***
	Yes	93	-0.34	
Round	Round 1	0	-	***
	Round 2	43	-	
	Round 3	42	0.10	
	Round 4	51	-0.13	
	Round 5	49	-0.08	
	Round 6	52	-0.36	
	Round 7	46	-0.27	
	Round 8	49	-0.13	
Cow	75 levels	-	-	-

* = $P < 0.05$; ** = $P < 0.01$; *** = $P < 0.001$.
DPS = dairy production system; DIM = days-in-milk; DM = dry matter; ME = metabolizable energy.

Table 3.9 Mean temperature-humidity index (THI) per season (n = 216).

	Monsoon	Winter	Dry season
THI	75.3 ± 1.8^{a}	71.5 ± 2.3^{b}	76.3 ± 2.7^{c}

Values with different subscript letters differ significantly at $P < 0.05$.

3.4 Discussion

The analysis of feeding strategies and resource utilization efficiency, measured as FCE, provides interesting insights on the impacts of urbanization on dairy production systems within the RUI of an emerging megacity such as Bengaluru in India. Yet, three methodological aspects have to be kept in mind when interpreting the results, since data collection took place on real farms (non-experimental DPU): i) quantification of refusals, although potentially large (5 to 10% when fed in a trough, 20 to 40% when fed directly on the grounds; FAO LEAP, 2016; Figure 3.8), was often not systematically possible; ii) quantification of feed intake in urban DPU (3 farms out of 7 in DPS-1) was difficult, as availability of market wastes fluctuated greatly and could include (non-)organic wastes discarded later. Therefore, feed intake and resulting calculations of CP and ME supply might be slightly overestimated in DPS-2, DPS-3 and DPS-4, while counterbalanced in DPS-1 by the slight underestimation of feed intake and resulting calculations of CP and ME supply in three DPU out of 7. Thirdly, ME and CP requirements for milk synthesis (L cows, all DPS) were based on milk offtake but not on milk production because the amount of milk ingested by the suckling calf could not be estimated. However, there was no difference between cMO of cows having a suckling calf and those who did not according to the stepwise regression. Therefore, supply status of lactating cows might be only slightly overestimated.

Figure 3.8 Refusals of green forage. Dairy producers often fed green forages as whole plants (stem with leaves) or chopped by hand, which leads to selective feeding of the most palatable parts and large amount of refusals.

The first insight from Bengaluru's case study is that forage offer to dairy cows and coverage of their nutritional requirements was not an issue according to the high intake and coverage values, despite seasonal change in the availability and quality of feedstuff; this was particularly the case when the management included at least partial reliance on self-cultivated forage combined with access to pasture (DPS-2 and DPS-3) or even without pasturing (DPS-4). Lack of own forage production (DPS-1) resulted in an extensive feeding management with large differences in ME and CP coverage from one cow to another but did not result in a systematic undersupply of cows. In comparison to intake values reported for stall feeding plus grazing systems in Mali (Amadou et al., 2015) and Burkina Faso (Schlecht et al., 2019), Bengaluru's dairy cows were fed far better and had DM intake values similar to cattle on intensive urban livestock farms in Niger (Diogo et al., 2010). High DM intake rates, daily use of concentrate feed and high prevalence of exotic genotypes point to a well-established dairy sector with respect to input supply (Duncan et al., 2013), market demand and infrastructures: on one hand, because many Indians are vegetarians (Government of India, 2014), milk and dairy products remain predominant diet components despite the general shift towards meat consumption that is usually associated with urbanization (Erler and Dittrich, 2017; Regmi and Dyck, 2001). On the other hand, rural dairy producers (DPS-2, DPS-3 and DPS-4) were well connected to Bengaluru's urban (milk) market through the strong network of settlement-based dairy cooperatives linked to the Karnataka Milk Federation (Cunningham, 2009), whereas urban dairy producers were often marketing some or all of their milk directly.

The second insight from Bengaluru's case study is that milk production leaves room for improvement. The average 10.9 kg MO per animal and day in Bengaluru's most intensive DPS is well above the reported milk yield of 5.9 kg per day for crossbred cattle in Bengaluru Urban District (National Dairy Development Board, 2015). The present average MO is however within the range of 6.7 to 11.0 kg milk offtake per day for European crossbred cows in Burkina Faso (Schlecht et al., 2019), despite higher feed intakes, ME and CP supply levels and prevalence of pure exotic genotypes in Bengaluru. Intensification of milk production relies on optimal feeding and breeding decisions (Diogo et al., 2013; Duncan et al., 2013) plus adequate health care. Concerning feeding, the low FCE of each of Bengaluru's DPS was well below the FCE range of large-scale dairy production in non-tropical countries: based on UK feeding standards, Beever and Doyle (2007) estimated a FCE range of 1.46 to 1.70 kg ECM kg^{-1} DM for a milk production range between 25 and 40 L day^{-1}; Bava et al. (2014) reported an FCE between 1.22 and 1.36 kg ECM kg^{-1} DM for a milk production range between 25 L day^{-1} and 29 L day^{-1} in three Italian DPS. The negative relationship between ME coverage ratios and cMO indicates potential for improvement through adjustment of the forage offer (Prasad et al., 2019). Prevalence of metabolic disorders (44%) within the herds due to unbalanced diets did not impacted cMO. Concerning animal genetics, native cattle produce on average 2.4 kg of milk per day (National Dairy Development Board, 2015), thus *exotic x native* multi-generation crossbreeds have a lower production potential than exotic cattle or first-generation exotic crossbreeds. *Cross-I* genotype was relevant for cMO, highlighting an F1 heterosis effect. Bengaluru's average THI across all seasons (74.3) characterizes a mild heat stress while the maximum recorded THI (82.5) characterizes severe heat stress (Moran, 2005). Despite the usual negative impact of heat stress on milk yield (West, 2003), THI could not be linked to cMO. Nevertheless, mastitis prevalence (21%) did also not impact cMO, despite being a major production disease. Yet mastitis needs to be tackled for animal welfare reasons.

The third insight from Bengaluru's case study is that distinct development pathways and levels of resource utilization efficiency coexisted within its RUI. Distinct pathways of intensification and extensification, coexisting within the same (peri-)urban areas, were similarly assessed in West African cities (Roessler et al., 2016) and in Bengaluru. They were distinguished by trade-offs at farm-level between land and (family) labour: on one hand, the most intensive dairy producers within Bengaluru's RUI (DPS-4) did not rely on pasture, which represented additional labour to self-cultivate forages or financial capital to buy forages. Semi-intensive dairy producers within Bengaluru's RUI (DPS-2 and DPS-3) relied on pasture thus allocating part of their labour to pasture rather than self-cultivation of forages, potentially decreasing the physical burden of cattle maintenance. The larger share of DMI from pasture in DPS-2 than in DPS-3 however yielded a lower MO. (Semi-)intensive feeding strategies yielded only marginal MO increases in DPS-3 and DPS-4 and low FCE. The large share of oversupplied cattle in DPS-2, DPS-3 and DPS-4 and dry pregnant cows and heifers in general, also reflected inefficiency in resource utilization. Although balancing their dairy diets would further reduce nutrient losses (Prasad et al., 2019), dairy producers self-cultivating forages made efficient use of cow manure by using it on their fields, thus enabling nutrient cycling at farm level. On the other hand, the most extensive dairy producers within Bengaluru's RUI (DPS-1) relied on pasture and green biomass growing on public grounds in rural areas or in urban areas, organic wastes from markets and non-cultivated green biomass growing around the numerous lakes of Bengaluru. This extensive feeding management was cheap and minimized labour related to cattle maintenance, which allowed a potential additional off-farm income-generating activity. Moreover, it yielded similar MO than (semi-)intensive feeding management (DPS-3 and DPS-4) and, by taking advantage of an abundant resource naturally available within the whole RUI, with a minimum resource expenditure, yielded the best FCE amongst the four DPS. At farm-level, the large difference in ME and CP coverage from one cow to another however showed that extensive feeding should be matched by an adequate knowledge of the cows' requirements. At landscape-level, potential pollution of Bengaluru's water bodies due to manure being washed away and neglection of the nutrient cycle due to the decoupling of crop and dairy production (Daburon et al., 2017; Prasad et al., 2019) showed that in urban areas, extensive feeding should be matched by an adequate manure management.

3.5 Conclusions

Bengaluru's case study sheds light on dairy production within an urbanizing environment leading to DPS with distinct feeding strategies, intensification levels and resource utilization efficiency. Extensive resource utilization by dairy producers across Bengaluru's RUI lead to higher efficiency in the conversion of ingested feed into milk. By opposition, rural DPS were (semi-)intensive, and if inputs within the dairy production unit increased, the inefficiency due to the oversupply of their cattle increased as well, thus their feed conversion efficiency dropped. To diminish inefficiencies in resources utilization, farmers should make better use of the production potential of exotic genotypes and increase cattle welfare: i) differential feeding at farm-level should be emphasized, especially regarding dry pregnant cows and mature heifer as these seem to be systematically oversupplied; ii) diet imbalances between energy and protein supply should be tackled; iii) husbandry conditions and hygiene practices should be upgraded to provide more protection again heat stress and to reduce mastitis prevalence. On the long term, for Bengaluru's authorities to support its dairy producers, i) feasibility of small-scale conservation of abundant green forage resources through drying or ensiling could be studied to reduce variation in forage availability and increase dairy farmers' resilience in periods of low forage availability; ii) feasibility of coupling of urban "landless" DPU with agricultural production elsewhere in Bengaluru's RUI could be studied to assure a better utilization of manure and preservation of the nutrient cycle.

A system approach to carbon footprint of dairy production in an urbanizing environment

4.1 Introduction

Greenhouse gas (GHG) emissions are an urgent global environmental problem, to which livestock supply chains contribute up to 15% (Gerber et al., 2013). Methane (CH_4) has a global warming potential 25 times bigger than carbon dioxide (CO_2; IPCC, 2007) and represents 44% of the sector's emissions, mostly emitted as part of the ruminants' digestive process, namely enteric fermentation (EF; Gerber et al., 2013). The manure management system (MMS) emits additional CH_4 and nitrous oxide (N_2O), which has a global warming potential 298 times bigger than CO_2 (IPCC, 2007). The global environmental impact of a livestock supply chain is calculated as CO_2 equivalents (CO_2-eq) released per unit of its output(s), mostly per kilogram milk or meat or both – in that case, one way to allocate the emissions (Baldini et al., 2017) is based on economic value of each output, another way to convert both products to edible protein e.g. in Gerber et al. (2011). Being the most common domestic ruminant species in the world (FAOSTAT, 2019), cattle contribute most to the sector's emissions, despite cow milk having a lower emission intensity than beef and milk or meat from small ruminants (Gerber et al., 2013). Yet, emission intensity of cow milk varies strongly within and between dairy production systems because productivity and emission intensity, especially of CH_4 and N_2O, are strongly correlated: as milk yield increases, emission intensity decreases. Hence, an improvement of diet quality and to a lesser extent the genetic makeup of the cows, achieve both productivity gains and emission reduction (Gerber et al., 2011). The global environmental impact of low-yielding milk production systems (< 2000 kg of milk per cow and year) is thus disproportionately high in comparison to the global environmental impact of high-yielding milk production systems, but the formers systems have more potential to mitigate CO_2-eq emissions by improving productivity at cow and herd level (Gerber et al., 2011; Gerber et al., 2013). Less productive dairy production systems (DPS) are typically found in the Global South, which globally host a higher number of lactating cows than developed countries, since the mostly small herds kept by a high share of the population comprise cows of indigenous breeds with low production potential (FAO, 2020a, 2020b). Since the 1990s, West Africa and Asia are rapidly urbanizing and in the Global South up to one third of milk is now produced by (peri-)urban DPS (FAO, 2020b; UN, 2018a), such as in Burkina Faso and Ghana (Dossa et al., 2015; Roessler et al., 2016), Ethiopia (D'Haene and D'Haese, 2019) or Egypt (Daburon et al., 2017). (Peri-)urban DPS alleviate the constraints of urban livestock husbandry (Butler, 2012) and of (peri-)urban areas where land is increasingly scarce and expensive, by the daily provision of a highly perishable and nutritionally important product (Schlecht et al., 2019). Coexisting (peri-)urban DPS in Ouagadougou, Burkina Faso, and in Tamale, Ghana, showed distinct trends of both, intensification and extensification of milk production (Roessler et al., 2016). Despite (peri-)urban DPS supplying primarily the demand on local milk markets, the GHG they emit have a global environmental impact. To assess the (global) environmental impact of dairy production systems, life cycle assessment (LCA) has become the method of choice, as it can, among others, account for a system’s intensification level (Bartl et al., 2011; Bava et al., 2014; Udo et al., 2016).

India is the second largest cow milk producer in the world since 1999, mostly because it also has the second largest cattle population in the world (FAOSTAT, 2019). Its dairy sector is dominated by smallholders: 80% of the dairy animals are kept in herds of 2 to 5 cows (Cunningham, 2009). Overall productivity is low: cows of the native breeds have a minimum average annual milk yield of 649 litres and a maximum of 818 litres, while crossbreeds between native and European cattle yield between 2190 litres (minimum average) and 2670 litres (maximum average) of milk per year (Duncan et al., 2013). In rural areas where dairy and crop production are coupled at farm level, manure is used on the fields as organic fertilizer and farmers cultivate forages themselves with little mechanization (Prasad et al., 2019). (Peri-)urban dairy production exists even in the biggest Indian cities (Delhi, Mumbai, Bengaluru) and is typically “landless”: (peri-)urban dairy producers do not cultivate land and rather than buying forages from rural areas they typically rely on locally available feed resources: public grounds are used as pasture, green biomass naturally growing around (peri-)urban lakes is harvested and fed on-farm and organic wastes from fruit and vegetable markets are also used as feedstuffs (Prasad et al., 2019). Because of the decoupling of dairy and crop production in (peri-)urban areas, however, manure management is problematic and nutrients contained therein are wasted (Prasad et al., 2019). Yet, the proximity to the city potentially improves market quality by easing the access of (peri-)urban dairy producers to production inputs and output marketing channels, enabling an intensification of their dairy production (Duncan et al., 2013).

Given that India has the largest dairy herd in the world, and hence, a massive contribution to global GHG emissions, in view of the correlation between productivity at farm level and emission intensity the following research question arises: does the emission intensity of four Indian DPS that coexist within the same urbanizing environment differ according to their intensification level and spatially explicit distribution? To answer this question, the emission intensity for each of the four previously identified DPS that coexist within Bengaluru's RUI (Chapter 2) was assessed as the carbon footprint (CF; all emissions calculated as CO_2-eq) of milk due to CH_4 and N_2O emissions from EF and MMS. Our dataset included 855 nutritional records from 147 dairy cattle, collected over one year, from four DPS previously identified in the rural-urban interface (RUI) of Bengaluru, India.

4.2 Materials and methods

4.2.1 Research area and dairy production systems

Bengaluru is the capital of the Indian southern state of Karnataka and one of the emerging megacities of these last decades: its population grew at a 4% annual rate in average between 2000 and 2018 and is currently over 10 million (United Nations, 2018b). Bengaluru's climate is hot semi-arid with a dry season (March-May) followed by a monsoon season (June-October) and winter (November-February). Monthly temperatures range between 18.5°C and 29.5°C and annual rainfall reaches 948 mm (average for 2013-2017, weather station data of the University of Agricultural Sciences Bangalore, GKVK campus). The administrative district of Bengaluru Urban has a bovine population of 145 000 heads (National Dairy Development Board, 2015). To assess dairy production practices in relation to the rapidly urbanizing environment, two research transects were established along a northern and a southern urban to rural gradient (Hoffmann et al., 2017) and 337 dairy production units (DPU) were surveyed. Four DPS (Table 3.1) were thus identified within Bengaluru's RUI based on three characteristics: i) a DPU's spatial location within Bengaluru's RUI as a proxy for the urbanization level (urban, peri-urban, rural) of its surroundings; ii) a DPU's feeding management: reliance, at least partially, on self-cultivated forages or pasture or both; and iii) a DPU's breeding management: cattle inflow (bought) or outflow (sold) or both within the herd, and genotypes kept. *Exotic* genotypes included Holstein Friesian (HF, 54% of all cattle in the survey) and Jersey (15%) cattle by opposition to *native* genotypes (10%; mostly *Bos indicus* Hallikar, a draught breed from the State of Karnataka producing 2.4 kg milk cow^{-1} day^{-1}; National Dairy Development Board, 2015). *Crossbreeds* (21%) ranged from *exotic* or *exotic x native* first-generation to multi-generation crosses. Dairy cattle were categorized as lactating cow, dry cow, heifer, young cattle (immature heifer) and calf (3-6 months old); a herd typically included 3.0 ± 1.5 cows (lactating or dry) plus mature heifers (pregnant or inseminated at least once) and 1.3 ± 1.2 non-productive dairy cattle (calves or immature heifers).

4.2.2 Data collection

Per DPS, seven DPU were selected (Chapter 3) and visited eight times at a 6-week interval between June 2017 and May 2018, further referred to as *round*. The length of each round was fixed across DPS but varied from one round to another: round 1 equalled 50 days, rounds 2 and 3 43 days, round 4 47 days, round 5 50 days, round 6 44 days, round 7 42 days, and round 8 46 days. Four DPU, one per DPS, were excluded because of incomplete datasets. Data were collected at cow-level with a focus on the DPU's feeding practices following Schlecht et al. (2019). Variables quantified at each visit for all dairy cattle included: 24-hour feedstuff offer (considered to equal daily feed intake at the farm, since refusals were often difficult to quantify because of DPU's feeding practices), pasture time, quality of feedstuffs (concentrations of dry matter (DM), metabolizable energy (ME), digestible organic matter (DOM), crude protein (CP), neutral detergent fibre (NDF) and acid detergent fibre (ADF); 321 analysed feed samples (for analytical procedures see section 3.2.3, for quality see Table 4.1), daily milk offtake (kg milk cow^{-1} day^{-1}), fat and protein content of milk, and heart girth of the animal (HG; in cm). Gross energy intake (GE) was calculated based on metabolizable energy intake and DOM (Chapter 3; Hales, 2019). Intake at pasture was estimated from eating time observed on pasture (Chapter 3) and an intake rate of 8 g DM per kg metabolic weight (Ayantunde et al., 2002). DOM of pasture biomass was based on the analysis of 32 samples of non-cultivated grasses (collected by dairy producers from public spaces for on-farm feeding) plus, in urban areas where cows had also access to household or market organic wastes dumped in the streets, 3 samples of vegetables and fruit mixes (weighted average value 50:50). Excretion of faeces (further referred to as manure) was calculated from the amount of DM ingested per day and DOM (kg manure cattle^{-1} day^{-1}). Individual body weight (BW), metabolic weight and daily weight gain (Δ kg BW day^{-1}), were calculated based on a HG to BW regression (kg BW = $-3.867 + 2.98 \times \log_{10}$ (HG); 569 weight records; $R^2 = 0.9846$; Grund, 2018). The date of last calving was asked for each cow in round 1 or, if calving occurred later, during the round following calving, while the length of dry and lactation period was calculated as an average for each DPS.

Table 4.1 Average concentration of dry matter (DM), crude protein (CP) content, neutral detergent fibre (NDF) content, acid detergent fibre (ADF) content, digestible organic matter (DOM) and gross energy (GE) content per type of feedstuff (n = number of feed samples).

Type of feedstuff	n	DM (% in FM)	CP (g kg^{-1} DM)	NDF (g kg^{-1} DM)	ADF (g kg^{-1} DM)	DOM (% in DM)	GE (MJ kg^{-1} DM)
Green forages	191	27	76	675	425	59	16.7
Dry forages	37	90	44	708	473	54	16.5
Crop residues, organic wastes	12	21	85	482	393	68	17.3
Concentrate feed	81	89	167	401	185	77	17.6
Pasture biomass	32	27	88	669	409	58	16.8
Urban pasture biomass	32:3*	19	92	562	363	68	17.3

FM: fresh matter; *weighted average value (50:50) of pasture biomass (32 samples) and urban organic biomass (3 samples of vegetable and fruit mixes).

4.2.3 GHG emissions, functional unit and allocation

The CF of the four DPS within Bengaluru's RUI was calculated as the sum of GHG in CO_2-eq of CH_4 (25 kg CO_2-eq kg^{-1} CH_4) and N_2O (298 kg CO_2-eq kg^{-1} N_2O). CF calculations included direct CH_4 emissions from EF and MMS, and direct and indirect N_2O emissions from MMS plus N losses due to volatilization of ammonia (NH_3) and nitrogen oxides ($NO_{x)}$ as well as leaching. The functional unit to which all emissions were related was one kg of energy-corrected milk (ECM; 1 kg ECM = kg milk x (0.25 + 0.122 fat % + 0.077 protein %; Sjaunja et al., 1990).

4.2.4 Computation of greenhouse gas emissions

GHG emissions were computed per dairy cattle and either round or year using Tier 2 approach according to IPCC guidelines (2006; Table 4.2). CH_4 emissions from EF were computed according to equation 10.21; for emission intensity factor (EIF) the default methane conversion factor (Y_m = 6.5 %) was used. MMS was 100% solid storage in all farms with a methane conversion factor (MCF) of 5% at an average ambient temperature equal to 25°C in and around Bengaluru (Table 10A-4, IPCC guidelines, 2006). CH_4 emissions from MMS were computed per dairy cattle and round according to equation 10.24 for volatile solid (VS) excretion, using the default urinary energy (0.04 GE) and ash content (0.08), and according to equation 10.23 for EIF using a maximum methane producing capacity for manure (B_0) of

0.13 (Table 10A-4, IPCC guidelines, 2006). The nitrogen consumption was computed according to equation 10.32, N retention according to equation 10.33 and N excretion according to equation 10.31. Direct N_2O emissions from MMS were computed according to equation 10.25. Indirect N losses from MMS due to volatilisation via NH_3 and NO_x were computed according to equation 10.26, N losses due to leaching according to equation 10.28, and indirect N_2O emissions due to volatilisation or leaching of N according to equations 10.27 and 10.29. The default value (0.005 kg N_2O-N kg^{-1} of N excreted; Table 10.21, IPCC guidelines, 2006) was used for EIF of direct N_2O emissions from solid storage MMS. The default value ($Frac_{GasMS}$ = 30%; Table 10.22, IPCC guidelines, 2006) was used for N volatilisation from MMS via NH_3 and NO_x. The default value ($Frac_{leach}$ = 30%; Table 11.3, IPCC guidelines, 2006) was used for N leaching from MMS during the rainy season. Because of the limited number of DPU replicates per DPS, methane and nitrous oxide emissions, milk offtake and CF were computed both per round and year. As round lengths were variable (see above), this introduced variability within DPS but did neither prevent comparison between DPS as the level of introduced variability was fixed across DPS, nor did it affect the calculated carbon footprint as the latter is a ratio. Results per round are discussed in detail, while an average result per year, irrespective of DPS, is used for comparison with other CF and whole LCA studies.

Table 4.2 Items computed, unit, equation number (#) in IPCC guidelines (2006) and parameter values used to calculate methane (CH_4) and nitrous oxide (N_2O) emissions.

Item	Unit	IPCC Equation #	Parameter value
CH_4 - Enteric fermentation			
Emission intensity factor	kg CH_4 $head^{-1}$ $round^{-1}$	10.21	Ym = 6.5%
CH_4 - MMS			
Volatile solid excretion rate	kg VS day^{-1}	10.24	Urinary energy = 0.04 GE Ash = 0.08
Emission intensity factor	kg CH_4 $head^{-1}$ $round^{-1}$	10.23	B_o = 0.13 MCF = 5% MS = 100%
N consumption	kg N $head^{-1}$ $round^{-1}$	10.32	
N retention	kg N $head^{-1}$ $round^{-1}$	10.33	
N excretion	kg N $head^{-1}$ $round^{-1}$	10.31	

Table 4.2 *- continued -*

Item	Unit	IPCC Equation #	Parameter value
N_2O - MMS			
Direct N_2O emissions	kg N_2O round^{-1}	10.25	MS = 100%
N Volatilisation in forms of NH_3 and NO_x	kg NH_3 and NO_x kg N round^{-1}	10.26	MS = 100% $Frac_{GasMS}$ = 30%
N Leaching	kg N round^{-1}	10.28	$Frac_{Leach}$ = 30%
Indirect N_2O emissions	kg N_2O round^{-1}	10.27; 10.29	

Bo = maximum methane producing capacity; $Frac_{GasMS}$ = percent of managed manure nitrogen that volatilises as NH_3 and NO_x; $Frac_{Leach}$ = percent of managed manure nitrogen losses due to runoff and leaching; GE = Gross energy; MCF = methane conversion factor in equation 10.23; MMS = manure management system; MS = fraction of manure handled in the considered MMS; N = Nitrogen; NH_3 = Ammonia ; NO_x = nitrogen oxides ; Ym.= methane conversion factor in equation 10.21

4.3 Results

4.3.1 Characteristics of dairy cattle

The heaviest lactating cows were found in DPS-1 (416 kg) and DPS-3 (410 kg; $P < 0.05$), and the lightest in DPS-2 (356 kg; $P < 0.05$), while lactating cows in DPS-4 had an intermediate body weight (396 kg; Table 4.4). The average weight gain (Δ BW) of lactating cow was 0.25 ± 0.33 kg day^{-1}. Daily milk production per lactating cow differed across DPS (Table 4.5). Thus, ECM offtake per DPU and round varied strongly across DPS, being lowest in DPS-2 (714 kg ECM; DPS-2 *versus* DPS-3 and DPS-4 $P < 0.05$; Table 4.7). Dairy producers in DPS-1 had a slightly higher ECM offtake (794 kg ECM; DPS-1 *versus* DPS-4, $P < 0.05$), followed by DPS-4 (1175 kg ECM) and DPS-3 (1260 kg ECM), whereby a high variation (± 903 kg ECM DPU^{-1} round^{-1}) was observed in the latter system. Annual milk production per cow ranged from a minimum of 2826 ± 1109 kg ECM L^{-1} year^{-1} in DPS-2 to a maximum of 4028 ± 1537 kg ECM L^{-1} day^{-1} in DPS-4 (Table 4.3) with an average of 3416 ± 1533 kg ECM L^{-1} day^{-1}. Lactation was shortest in DPS-3 and DPS-4 with 356 days and longest in DPS-1 with 414 days. In consequence, the dry period was shortest in DPS-3 with 77 days and longest in DPS-2 with 91 days.

Due to their pregnancy, dry cows were heavier than lactating cows, with their BW ranging from a minimum of 370 kg in DPS-1 to a maximum BW of 427 kg in DPS-4. They also gained more weight per day, on average 0.29 ± 0.27 kg day^{-1}. Heifers were lighter than most lactating and dry cows or of similar BW to the lightest of them, with BW ranging from 307 kg in DPS-3 to 382 kg in DPS-1, and an average growth rate (Δ BW) of 0.27 ± 0.35 kg day^{-1}. Young cattle and calves were of course much lighter: BW of young cattle ranged from 114 kg in DPS-2 to 180 kg in DPS-4, with a daily Δ BW of 0.30 ± 0.36 kg day^{-1}. BW of calves ranged from 63 kg in DPS-2 to 103 kg in DPS-1, their BW gain averaged 0.20 ± 0.27 kg day^{-1} (Table 4.4).

Table 4.3 Average length of dry period and lactation (in days), average protein content of milk, annual milk offtake (kg energy-corrected-milk (ECM)) per cow and year, and annual manure production per dairy production unit (DPU) and year, for each dairy production system (DPS).

DPS	Length		Milk offtake		Manure (kg DPU^{-1} year^{-1})
	Dry period	Lactation	Protein %	kg ECM cow^{-1} year^{-1}	
DPS-1	85	414	3.10 ± 0.19^{a}	3144 ± 837	3787
DPS-2	91	359	3.01 ± 0.17^{b}	2826 ± 1109	4544
DPS-3	77	356	3.06 ± 0.18^{ab}	3665 ± 2342	8369
DPS-4	78	356	3.09 ± 0.18^{a}	4028 ± 1537	7505

Values with different superscript letters within the same column differ significantly at $P < 0.05$.

4.3.1 Feedstuffs and diet

Common green forages included African tall maize (*Zea mays*), hybrid Napier grass (*Pennisetum glaucum* × *P. purpureum)* and a wide range of wild (non-cultivated) grasses collected from green spaces and, in urban areas, also from the surroundings of lakes. Green forages had an intermediate concentration of CP (76 g kg^{-1} DM) and fibre (675 g NDF kg^{-1} DM, 425 g ADF kg^{-1} DM), resulting in a content of 59% DOM and 16.7 MJ GE kg^{-1} DM (Table 4.1). The share of green forages in the diet of dairy cattle differed across DPS but also within herds (Table 4.5). Overall, it represented the main forage type of each dairy cattle category in DPS-2, DPS-3 and DPS-4, ranging from 30% for dry cows in DPS-2 up to 91% for calves in DPS-3. The share of green forages in the diet of dairy cattle in DPS-1 was lower, ranging from 26% to 33%, except for calves (72%). During winter and especially the dry season, dairy producers compensated the reduced availability of green forages due to low water availability by feeding dry forages. Dry forages were commonly straw of finger millet (*Eleusine coracanal*, known locally as *ragi*) and occasionally dried maize (straw without cobs). Dry forages were poor in CP (44 g kg^{-1} DM) but rich in fibre (708 g NDF kg^{-1} DM, 473 g ADF kg^{-1} DM). Thus, at 54%, DOM of dry forages was the lowest of all types of feedstuffs, and their average GE content was 16.5 MJ kg^{-1} DM (Table 4.1). Except for lactating cows, the dietary share of dry forages did neither differ between DPS nor within herds, except for those of DPS-3 (Table 4.5). Overall, the share of dry forage ranged from 0% for calves in DPS-1 to 28% for dry cows in DPS-2.

Table 4.4 Average weight and number of records (n) per cattle category and per dairy production system (DPS) with standard error of the mean (SEM; n total = 873), and average daily weight gain per cattle category with standard error of the mean (n total = 754).

DPS	Body weight (kg)									
	n	Lactating cow	n	Dry cow	n	Heifer	n	Young	n	Calf
DPS-1	97	416^{b}	12	413^{ab}	19	382^{a}	29	135^{a}	8	103^{a}
DPS-2	97	356^{a}	16	370^{a}	11	322^{ab}	41	114^{b}	18	63^{b}
DPS-3	132	410^{bc}	37	427^{ab}	29	307^{b}	53	150^{c}	20	71^{b}
DPS-4	112	396^{c}	24	424^{b}	19	376^{a}	50	180^{d}	14	73^{b}
SEM		*3.0*		*7.6*		*8.6*		*4.3*		*2.5*
Weight gain (Δ kg BW day^{-1})	349	0.25 ± 0.33	67	0.29 ± 0.27	68	0.27 ± 0.35	173	0.30 ± 0.36	60	0.20 ± 0.27
SEM		*0.02*		*0.03*		*0.04*		*0.03*		*0.04*

Body weight values with different superscript letters within the same column differ significantly at $P < 0.05$.

Table 4.5 Average number of dairy cattle (n) per DPU, average daily energy-corrected milk (ECM) offtake per lactating cow, share of dry matter (DM) intake per type of feedstuff and average total daily DM intake per cattle category and dairy production system (DPS; n observations = 856).

Cattle category and DPS	n	ECM (kg cow^{-1} day^{-1})	Share of dry matter intake per type of feedstuff (%)					Daily feed intake (kg DM cattle^{-1} day^{-1})
			Green forages	Dry forages	Special	Concentrate feed	Pasture	
Lactating cow								
DPS-1	2.0 ± 0.8	7.70 ± 3.32^{a}	28^{a}	11^{a}	15^{a}	24$^{a\,A}$	22$^{a\,A}$	10.8 ± 4.94^{a}
DPS-2	2.0 ± 0.9	8.59 ± 3.65^{a}	41$^{b\,A}$	11^{a}	0^{b}	26$^{a\,A}$	22$^{a\,A}$	11.7 ± 3.16^{a}
DPS-3	2.8 ± 1.7	10.06 ± 4.00^{b}	42$^{b\,A}$	15$^{b\,A}$	1^{b}	29$^{b\,A}$	13$^{b\,A}$	14.0 ± 3.82^{b}
DPS-4	2.3 ± 1.1	11.06 ± 4.50^{b}	46$^{b\,A}$	14^{ab}	1^{b}	37$^{c\,A}$	2^{c}	15.8 ± 4.45^{c}

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Table 4.5 *- continued -*

Cattle category and DPS	n	ECM (kg cow^{-1} day^{-1})	Share of dry matter intake per type of feedstuff (%)					Daily feed intake (kg DM cattle^{-1} day^{-1})
			Green forages	Dry forages	Special	Concentrate feed	Pasture	
Dry cow								
DPS-1	0.3 ± 0.5^{a}		30	11	11^{a}	21^{A}	27$^{a\ A}$	10.1 ± 4.99^{a}
DPS-2	0.3 ± 0.5^{a}		30^{A}	28	0^{b}	23^{A}	19$^{a\ AB}$	13.2 ± 4.25^{ab}
DPS-3	0.9 ± 1.0^{b}		45^{A}	17^{AB}	1^{b}	24^{B}	13$^{a\ A}$	12.1 ± 4.11^{ab}
DPS-4	0.5 ± 0.7^{ab}		46^{A}	21	0^{b}	31^{AB}	2^{b}	15.4 ± 3.08^{b}
Heifer								
DPS-1	0.4 ± 0.6		26^{a}	15*	1	21^{A}	37$^{a\ A}$	8.9 ± 3.54^{a}
DPS-2	0.2 ± 0.4		47$^{ab\ AB}$	4*	0	18^{AB}	31$^{a\ A}$	8.4 ± 2.27^{a}
DPS-3	0.6 ± 1.0		57$^{b\ AB}$	17*^{AB}	0	25^{B}	1$^{b\ B}$	10.4 ± 4.79^{ab}
DPS-4	0.4 ± 0.8		76$^{c\ B}$	1*	0	23^{B}	0^{b}	13.3 ± 2.59^{b}
Young								
DPS-1	0.6 ± 1.1		33^{a}	15	22^{a}	5^{B}	25$^{a\ A}$	3.5 ± 3.08^{a}
DPS-2	0.9 ± 0.7		61$^{b\ B}$	18	0^{b}	11^{B}	10$^{b\ BC}$	4.3 ± 2.15^{a}
DPS-3	1.3 ± 1.2		63$^{b\ B}$	8^{B}	0^{b}	11^{C}	18$^{b\ AB}$	4.7 ± 2.87^{a}
DPS-4	1.0 ± 1.1		50$^{b\ AB}$	24	0^{b}	22^{B}	4^{b}	5.7 ± 2.12^{b}
Calf								
DPS-1	0.2 ± 0.4		72^{ac}	0	3	25^{AB}	0^{B}	1.9 ± 1.17
DPS-2	0.4 ± 0.5		82$^{a\ C}$	10	0	8^{B}	0^{C}	1.4 ± 0.95
DPS-3	0.4 ± 0.6		91$^{b\ C}$	9^{AB}	0	0^{D}	0^{B}	1.2 ± 0.86
DPS-4	0.3 ± 0.5		41$^{c\ AB}$	19	9	31^{B}	0	1.6 ± 1.06

Values within a column with different lowercase (DPS) or capital (category of dairy cattle) subscript letters differ significantly at $P < 0.05$.

*Significant differences between DPS but number of observations is too low to discern pairwise differences.

Overall, the dry forages' share ranged from 0% for calves in DPS-1 to 28% for dry cows in DPS-2. Special feedstuffs such as crop residues and organic wastes – vegetable or fruit wastes from markets – were fed almost only by dairy producers in DPS-1. Crop residues and organic wastes were rich in CP (85 g kg^{-1} DM) and low in fibre (482 g NDF kg^{-1} DM, 393 g ADF kg^{-1} DM); thus their DOM and GE contents were 68% DOM and 17.3 MJ GE kg^{-1} DM (Table 4.1). The share of special feedstuffs in the diet ranged from 1% for calves up to 22% for young cattle in DPS-1, while in the other DPS they did not contribute more than 9% of the diet (calves in DPS-4; Table 4.5). Dairy producers used a large variety of concentrate feed - wheat flour, with or without bran, corn flour, dairy pellets, chickpea husks (*Cicer arietinum*, known as *Bengal gram*) and groundnut cake - to which they usually added raw salt or a mineral mixture. Overall, concentrate feed had the highest CP (167 g kg^{-1} DM) and the lowest fibre content (401 g NDF kg^{-1} DM, 185 g ADF kg^{-1} DM). Thus, DOM of concentrate feed was the highest (77%) amongst all types of feedstuffs and so was their GE content (17.6 MJ kg^{-1} DM; Table 4.1). The dietary share of concentrate feed differed across DPS and within herds (Table 4.5). Overall, lactating cows received the highest share of concentrate feed and across DPS, this share was highest in DPS-4 (37%) followed by DPS-3 (29%), while dairy producers in DPS-2 and DPS-1 fed less concentrate feed to their lactating cows (26% and 24%; DPS-4 *versus* DPS-3 *versus* DPS-1 and DPS-2 $P < 0.05$). Dry cows received on average one quarter of their diet in the form of concentrate feed and heifer slightly less (22%). Young cattle received barely any concentrate feed (average 13%), while calves received proportionally more in DPS-1 (25%) and DPS-4 (31%) but almost nothing in DPS-2 (8%) and DPS-3 (0%). As the quality of pasture biomass was estimated from samples of wild grasses, its nutritional value was similar to those of collected green forages (Table 4.1). In the urban DPS, feed intake during pasturing also included organic market wastes, the quality of this combined feed source was of higher CP (92%) and lower fibre content (562 g NDF kg^{-1} DM, 363 g ADF kg^{-1} DM; Table 4.1) than pasture biomass. In consequence, DOM and GE contents of urban pasture biomass were higher (68% DOM, 17.3 MJ GE kg^{-1} DM) than of peri-urban and rural pasture biomass. Since dairy producers in DPS-4 did not send their cattle to pasture, the share of pasture biomass in cattle's diet differed across DPS and within herds, because calves were never sent to pasture (Table 4.5). Yet, even amongst dairy producers sending their cattle to pasture, the dietary share of pasture-based forage varied between cattle in DPS-1 and DPS-2 (range 10% to 37%, calves excluded) and cattle in DPS-3 (range 1% to 18%, calves excluded; DPS-1 and DPS-2 *versus* DPS-3 $P < 0.05$ for lactating cows and heifers, DPS-1 *versus* DPS-2 and DPS-3 $P < 0.05$ for young cattle; no difference for dry cows; Table 4.5).

4.3.2 Methane emissions of Bengaluru's dairy production systems

Methane emissions (per DPU and round) due to EF significantly differed between DPS: they were low in the extensive DPS-1 (23 ± 14 kg CH_4) and semi-intensive DPS-2 (25 ± 10 kg CH_4), but much higher in the semi-intensive DPS-3 (53 ± 23 kg CH_4) and intensive DPS-4 (50 ± 31 kg CH_4; DPS-1 and DPS-2 *versus* DPS-3 and DPS-4 $P < 0.05$; Table 4.7 and Figure 4.1). Despite the extent of methane emissions due to MMS (per DPU and round) being smaller, they likewise differed between DPS: low MMS emissions were calculated for the extensive DPS-1 (1.63 ± 1.11 kg CH_4) and semi-intensive DPS-2 (1.86 ± 0.85 kg CH_4), and high values for the semi-intensive DPS-3 (4.05 ± 1.87 kg CH_4) and the intensive DPS-4 (3.76 ± 2.37 kg CH_4; DPS-1 and DPS-2 *versus* DPS-3 and DPS-4 $P < 0.05$; Table 4.7 and Figure 4.1).

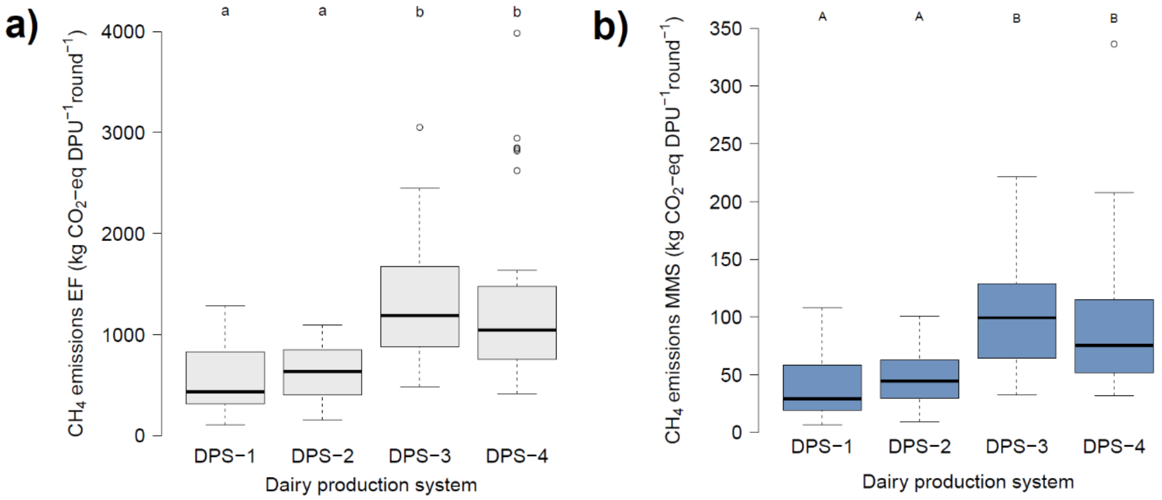

Figure 4.1 Methane (CH_4) emissions per dairy production unit (DPU) and round due to a) enteric fermentation (EF) and b) manure management system (MMS) in carbon dioxide equivalents (kg CO_2-eq) for each dairy production system (DPS) in Bengaluru's rural-urban interface. Please note the different scaling of the y-axes. The black line shows the median value for each group, the box the interquartile range, the whiskers the first and third quartiles and the circles are outlier values. Boxplots with different lowercase (CH_4 emissions EF) or uppercase (CH_4 emissions MMS) superscript letters differ significantly at $P < 0.05$ (n= 192).

Dairy producers in DPS-4 did not send their dairy cattle to pasture but relied, at least partially, on self-cultivated forages. Despite being labour-intensive, this feeding management resulted in the highest DM intake per kg MW and day for LDH ($P < 0.05$; Table 3.3) and the highest net DM intake per lactating cow and day with 15.8 ± 4.45 kg DM offered ($P < 0.05$; Table 4.5). Dairy producers in DPS-3 sent their cattle to pasture and relied, at least partially, on self-cultivated forages too. This feeding management resulted in an intermediate DM intake per kg MW and day for their LDH, similar to the DM intake per kg MW and day in DPS-2, which had the same feeding management (Table 3.3). For the net DM intake per lactating cow and day, dairy producers in DPS-3 yielded the second highest values with 14.0 ± 3.82 kg DM ($P < 0.05$; Table 4.5). Thus, methane emissions per DPU and round due to EF were lower in DPS-2 than in DPS-3. The lower BW of LDH cattle in DPS-2 explains why DM intake per kg MW was similar in DPS-2 and DPS-3 (Table 3.3). In contrast to dairy producers in DPS-4, the dairy producers in DPS-1 practiced extensive feeding since they relied on pasture and did not cultivate forages. This feeding management resulted the lowest DM intake per kg MW and day for LDH (Table 3.3), especially since their cattle were amongst the heaviest (Table 4.4). Daily net DM intake per lactating cow was low with 10.8 ± 4.94 kg DM (DPS-1 and DPS-2 *versus* DPS-3 *versus* DPS-4 $P < 0.05$; Table 4.5). Thus, methane emissions per DPU and round due to EF were lower in DPS-1 than in DPS-3 and DPS-4 (Table 4.7).

To a lesser extent, higher methane emissions can also be linked to a higher number of dairy cattle, especially in DPS-3. Only the number of dry cows differed between DPS, with DPU in DPS-3 having on average 0.9 ± 1.0 dry cows in their herd *versus* 0.3 ± 0.5 in DPS-1 and DPS-2 ($P < 0.05$) while DPU in DPS-4 kept an intermediate number of 0.5 ± 0.7 dry cows (Table 4.5). Despite non-significant differences, DPUs in DPS-3 systematically kept the highest average numbers of lactating cows, heifers and young per herd and round, which contributed to higher methane emission values (Table 4.5).

Concerning forage quality and its relation to methane emissions due to MMS, both special feedstuffs and concentrate feed had high GE and DOM concentrations. In line with the fact that special feedstuffs were mostly fed in DPS-1 (Table 4.5), the weighted average DOM of the diet of lactating cows, heifers and young cattle was highest in DPS-1 ($P < 0.05$). The weighted average DOM was however similar across DPS for the diet of dry cows (Table 4.6). Higher weighted average DOM in DPS-1 thus partly contributed to its low methane emissions due to MMS. Diet quality was similar for each dairy cattle category in DPS-1 but varied in the other DPS: in line with the fact that concentrate feed were fed mostly to LDH (Table 4.5), the weighted average DOM of the diet of lactating cows was higher than for heifers or young cattle or both ($P < 0.05$; Table 4.6), while dry cows and calves had an intermediate diet quality (Table 4.6). The overall contribution of each dairy cattle category to EF methane emissions (per head) decreased with decreasing BW and feed intake: cattle contributing most to EF emissions per round were milking cows (10.72 ± 1.43 kg CH_4) and dry cows (10.18 ± 0.83 kg CH_4; $P < 0.05$), followed by heifers (8.38 ± 1.23 kg CH_4), young cattle (3.76 ± 0.46 kg CH_4) and finally calves (1.29 ± 0.23 kg CH_4).

As the share of the different types of feedstuffs varied per cattle type within a herd, average DOM also varied and excretion rates of VS of heifers were thus similar to those of milking and dry cows. In consequence, MMS methane emissions (per head and round) did not differ between milking cows (0.78 ± 0.11 kg CH_4), dry cows (0.78 ± 0.07 kg CH_4) and heifers (0.67 ± 0.12 kg CH_4). Those of young cattle (0.30 ± 0.03 kg CH_4) and calves (0.10 ± 0.02 kg CH_4) were however lower (milking cows, dry cows and heifers *versus* young cattle *versus* calves $P < 0.05$).

Table 4.6 Number of observations (n) and diet quality (weighted average of digestible organic matter DOM, %) per dairy production system (DPS) and category of dairy cattle with standard error of the mean (SEM).

DPS	Diet quality (weighted average DOM%)									
	n	Lactating cow	n	Dry cow	n	Heifer	n	Young	n	Calf
DPS-1	97	68^{a}	13	68	19	67^{a}	29	70^{a}	7	6^{*}
DPS-2	97	$65^{b\ A}$	16	62^{AB}	11	$63^{ab\ AB}$	39	$60^{b\ B}$	17	$62^{*\ AB}$
DPS-3	132	$64^{b\ A}$	43	62^{AB}	30	$61^{b\ B}$	50	$60^{b\ B}$	18	$59^{*\ B}$
DPS-4	112	$65^{b\ A}$	25	63^{AB}	19	$59^{b\ B}$	50	$61^{b\ B}$	12	$66^{*\ AB}$
SEM		*0.26*		*0.63*		*0.70*		*0.55*		*0.94*

Values within a column with different lowercase (DPS) subscript letters differ significantly at $P < 0.05$.
Values within a row with different capital (category of dairy cattle) subscript letters differ significantly at $P < 0.05$.
*Significant analysis of variance across DPS but data is not enough to discern pairwise differences.

4.3.3 Nitrous oxide emissions of Bengaluru’s dairy production systems

As for methane emissions, N_2O losses were each time lower in DPS-1 and DPS-2 than in DPS-3 and DPS-4 ($P < 0.05$; Table 4.7). Total N_2O emissions ranged from 0.17 kg N_2O DPU^{-1} $round^{-1}$ in DPS-1 to 0.38 kg N_2O DPU^{-1} $round^{-1}$ in DPS-4. In CO_2-eq N_2O contribution ranged from 51 kg C_2O-eq DPU^{-1} $round^{-1}$ in DPS-1 to 113 kg C_2O-eq DPU^{-1} $round^{-1}$ in DPS-4 (Figure 4.2). N_2O contributed 7 to 8% of total DPU emissions per round (DPS-4; Table 4.7).

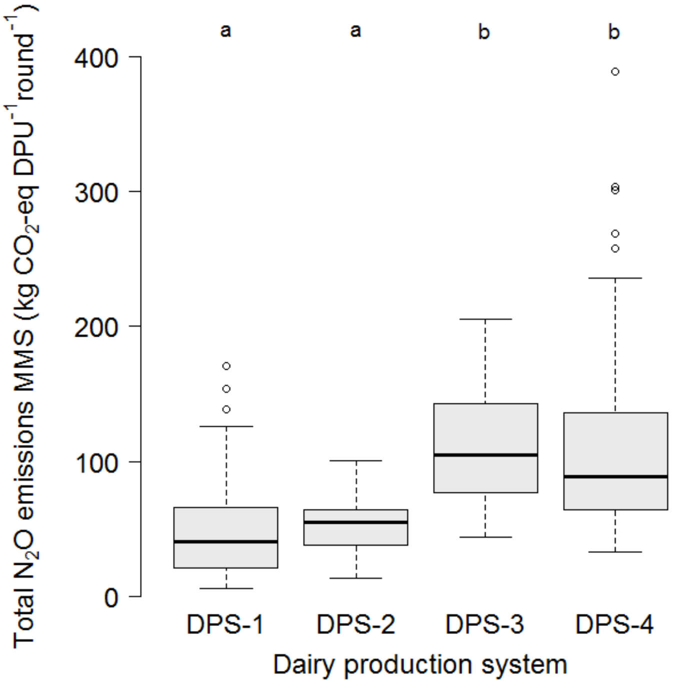

Figure 4.2 Total nitrous oxide (N_2O) emissions per dairy production unit (DPU) and round, expressed as carbon dioxide equivalents (kg CO_2-eq) for each dairy production system (DPS) in Bengaluru's rural-urban interface. The black line shows the median value for each group, the box the interquartile range, the whiskers the first and third quartiles and the circles are outlier values. Boxplots with different lowercase superscript letters differ significantly at $P < 0.05$ (n= 192). DPU = dairy production unit; MMS = manure management system.

4.3.4 Carbon footprint of Bengaluru's dairy production systems

Overall, DPS-1 and DPS-2 showed low methane and nitrous oxide emissions as well as low ECM offtake per DPU and round, while DPS-3 and DPS-4 were characterized by high methane and nitrous oxide emissions, and a high ECM offtake per DPU and round. Computation of GHG emissions and ECM offtake per DPU and round resulted in 189 observations of CF across the studied DPUs. Three observations (two in DPS-3 and one in DPS-4) of ECM per DPU and round equalled zero (no lactating cow in the DPU on the day of data collection), preventing the calculation of the ratio between GHG emissions and ECM offtake for these specific cases. The results on the CF ratio between GHG emissions and ECM offtake reflected the variations across DPS in methane and nitrous oxide emissions and ECM offtake: CF (in kg CO_2-eq kg^{-1} ECM) was lowest in DPS-1 with a ratio of 0.91 ± 0.59 and higher in DPS-2 (1.21 ± 0.69), DPS-3 (1.95 ± 1.85) and DPS-4 (1.52 ± 1.05; DPS-1 *versus* DPS-2, DPS-3 and DPS-4 $P < 0.05$; Figure 4.3). Outliers existed for all DPS; they were not systematically caused by the same DPU in a DPS but rather explained by the variation in milk offtake per DPU across the year. DPS-3 showed again a greater variability in CF than the other DPS and included the highest values (8.54 kg CO_2-eq kg^{-1} ECM). In this specific DPS, mastitis prevalence was severe and regular, which strongly decreased milk offtake in some rounds and resulted in a high CF.

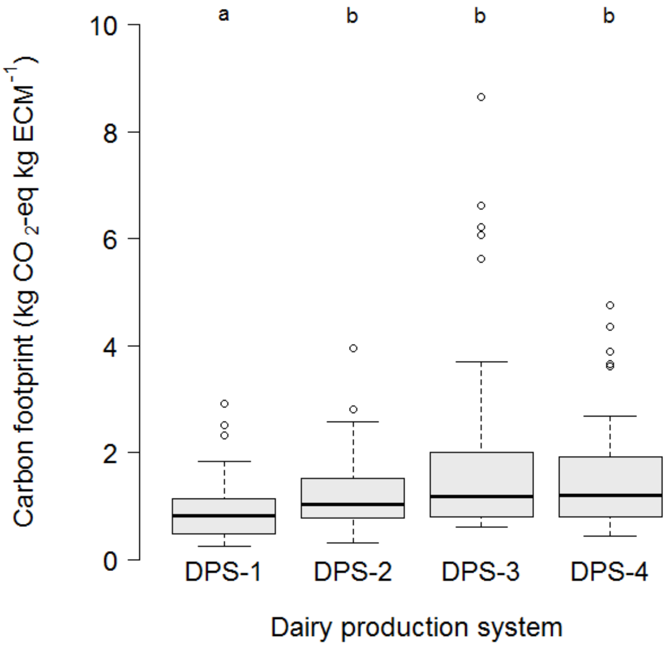

Figure 4.3 Carbon footprint per dairy production unit and round, expressed as ratio between carbon dioxide equivalents (kg CO_2-eq) and milk offtake (kg energy-corrected milk (ECM)) for each dairy production system (DPS) in Bengaluru's rural-urban interface. The black line shows the median value for each group, the box the interquartile range, the whiskers the first and third quartiles and the circles are outlier values. Boxplots with different lowercase superscript letters differ significantly at $P < 0.05$ (n= 189).

When computed per year, the number of replicates decreased to six per DPS. Thus, it was only possible to detect a significant difference across DPS for methane emissions due to EF and MMS per DPU and year, but data did not allow detecting pairwise differences (Table 4.8). Regarding both ECM offtake and CF per DPU and year, there was no significant variation across DPS. CF per year was lower than CF per round and, despite no significant difference, showed the same pattern as CF (kg CO_2-eq kg^{-1} ECM) per round: low CF in DPS-1 (0.82 ± 0.32), intermediate CF in DPS-2 (1.07 ± 0.24) and DPS-4 (1.26 ± 0.44) and highest CF in DPS-3 (1.43 ± 0.54). The difference between the lowest and the highest CF was smaller when computed per year (CF of DPS-3 = 1.7 x CF of DPS-1) than when computed per round (CF of DPS-3 = 2.1 x CF of DPS-1).

Table 4.7 Methane (CH_4) and nitrous oxide (N_2O) emissions per dairy production unit (DPU) and round, contribution in CO_2-equivalents to the total GHG emissions per DPU and round, milk offtake (kg energy-corrected-milk (ECM)) per DPU and round and carbon footprint for each dairy production system (DPS).

DPS	Methane emissions (kg CH_4 DPU^{-1} $round^{-1}$)		Nitrous oxide emissions (kg N_2O DPU^{-1} $round^{-1}$)				Contribution CO_2-eq (%)		Milk production (kg ECM DPU^{-1} $round^{-1}$)	CF (kg CO_2-eq kg^{-1} ECM)
	EF	MMS	MMS_{direct}	Volatilization	Leaching	$MMS_{indirect}$	CH_4	N_2O		
DPS-1	23 ± 14^{a}	1.63 ± 1.11^{a}	0.1 ± 0.1^{a}	3 x $10^{-2\ a}$	3 x $10^{-2\ a}$	9 x $10^{-4\ a}$	92	8	794 ± 380^{ab}	0.91 ± 0.59^{a}
DPS-2	25 ± 10^{a}	1.86 ± 0.85^{a}	0.1 ± 0.1^{a}	4 x $10^{-2\ a}$	3 x $10^{-2\ a}$	1 x $10^{-3\ a}$	93	7	714 ± 367^{a}	1.21 ± 0.69^{b}
DPS-3	53 ± 23^{b}	4.05 ± 1.87^{b}	0.2 ± 0.1^{b}	8 x $10^{-2\ b}$	6 x $10^{-2\ b}$	2 x $10^{-3\ b}$	93	7	1260 ± 903^{bc}	1.95 ± 1.85^{b}
DPS-4	50 ± 31^{b}	3.76 ± 2.37^{b}	0.2 ± 0.2^{b}	8 x $10^{-2\ b}$	6 x $10^{-2\ b}$	2 x $10^{-3\ b}$	92	8	1175 ± 638^{c}	1.52 ± 1.05^{b}

Values within a column with different superscript letters differ significantly at $P < 0.05$.

Table 4.8 Annual methane and nitrous oxide emissions in CO_2-equivalents per dairy production system (DPS) in Bengaluru's rural-urban interface.

DPS	Methane emissions (kg CH_4 DPU^{-1} $year^{-1}$)		Nitrous oxide emissions (kg N_2O DPU^{-1} $year^{-1}$)				Contribution CO_2-eq (%)		Milk production (kg ECM DPU^{-1} $year^{-1}$)	CF (kg CO_2-eq kg^{-1} ECM)
	EF	MMS	MMS_{direct}	Volatilization	Leaching	$MMS_{indirect}$	CH_4	N_2O		
Overall	302 ± 178	23 ± 14	1.3 ± 0.8	0.5 ± 0.3	0.4 ± 0.2	0.01 ± 0.01	92	8	7886 ± 4151	1.14 ± 0.44
DPS-1	182 ± 97*	13 ± 8*	0.8 ± 0.5*	0.3 ± 0.2*	0.3 ± 0.2*	0.01 ± 0.00*	92	8	6353 ± 1691	0.82 ± 0.32
DPS-2	203 ± 61*	15 ± 5*	0.9 ± 0.3*	0.3 ± 0.1*	0.3 ± 0.1*	0.01 ± 0.00*	93	7	5711 ± 2241	1.07 ± 0.24
DPS-3	421 ± 142*	32 ± 12*	1.7 ± 0.5*	0.7 ± 0.2*	0.5 ± 0.1*	0.02 ± 0.00*	93	7	10079± 6442	1.43 ± 0.54
DPS-4	402 ± 233*	30 ± 17*	1.8 ± 1.2*	0.7 ± 0.5*	0.6 ± 0.4*	0.02 ± 0.01*	92	8	9399 ± 3586	1.26 ± 0.44

*Significant analysis of variance across DPS but data is not enough to make statements about pairwise differences.

4.4 Discussion

LCA is an important resource to assess and compare the global environmental impact of dairy production systems across the world. LCA must however balance accuracy and representativeness, which in particular applies to LCA of small-scale tropical DPS, where inhomogeneous management practices across DPU and variability of inputs and outputs within DPU is common. As in the present study data were computed per DPU, two methodological constraints apply:

The first methodological constraint is that collection of sufficient data to correctly estimate the CF of a small-scale tropical DPU is time intensive and, in a system's approach, limits the number of replicates. Weiler et al. (2014) included 20 farms in their LCA, which is less than our sample size, but they did not distinguish between them. Cerri et al. (2016) included 22 farms in their LCA and distinguished two groups based on the size of their herds. As this research focused on the identification and characterization of distinct co-existing DPS within Bengaluru's RUI (Chapter 2), the system's approach was retained for computing CF but limited statistical power of the results as there were only six observations per DPS, one for each DPU. By computing emissions per round, which was our original time frame, rather than per year, the number of observations per farm increased from one to eight, i.e. 48 observations per DPS, and allowed for conclusive analysis of variance and pairwise comparison. Yet, the advantage of computing CF by round rather than year (increased number of observations per DPS) was greater than the disadvantage (enhanced variation due to unequal round length). Significant differences at round-level showed that even within a relatively small geographical space and short time frame, distinct farm management practices resulted in distinctly different CF. If the number of replicates per DPS had been higher, significant differences would also have shown in CF computed per year. For comparison of the present data with other studies, the yearly average CF across DPS of 1.17 kg CO_2-eq kg^{-1} ECM will be used. The second methodological constraint is that, since the values were computed per real non-experimental DPU, the overall sample and its representativeness are small at the scale of India, which hosts the largest dairy herd in the world and support the livelihood of 70 million dairy household across a huge and diverse geographical region (Cunningham, 2009; FAOSTAT, 2019). Nevertheless, the present sample is representative of distinct and co-existing DPS within the RUI of an emerging Indian megacity, such as Bengaluru, Delhi or Mumbai. It shows that CF of different DPS differ according to their intensification level and spatial distribution within a relatively small geographical area such as the rural-urban interface of a megacity. To our knowledge, the CF of DPS in an urbanizing environment have not yet been documented elsewhere.

Apart from these initial methodological considerations, the present study was limited in one minor and one major aspect: regarding the minor limitation, a six-week interval captures variation in nutrition management well enough but results in rough milk production estimations for one round, especially in tropical smallholder dairy production units with few replicates at cow-level, highly variable production and suckling calves, which results in milk offtake value rather than true milk yield. In three instances CF per DPU and round could not be computed because on the day of data collection, no cow was lactating. Thus, a milk offtake equalling zero was computed for the round while in reality some milk might have been produced during the duration of the round, which would have resulted in a high CF rather than a missing observation. Hence, computation of CF for a short time frame, especially in the context of smallholder dairy production, could be improved by modelling of representative lactation curves (see Zezza et al. (2016) for a potential methodology). Regarding its major limitation, the collected data focused on nutrition at cow-level. Thus, general data collected at farm-level were insufficient to compute a cradle-to-farm-gate LCA and limited GHG computations to CF caused by the farm's dairy herd, namely methane emissions due to EF and MMS, and nitrous oxide emissions due to MMS. Cerri et al. (2016) reported that emissions from livestock accounted for 89 to 98% of the cradle-to-farm-gate GHG emissions of Brazilian beef production units. In Peru, emissions from livestock accounted for respectively 74% and 82%, of cradle-to-farm-gate emissions in an intensive and extensive dairy production system (Bartl et al., 2011). Bengaluru' DPS share similarities with both DPS described by Bartl et al. (2011) but are also different in a few aspects, which prevents direct comparison. Using their computations as threshold values, however, it can roughly be estimated that the cradle-to-farm-gate CF of an average DPU with EF and MMS emissions of 1.17 kg CO_2-eq kg^{-1} ECM ranges between 1.43 and 1.58 kg CO_2-eq kg^{-1} ECM.

The quantification of the global environmental impact of Bengaluru' DPS through CF of milk provides interesting insights into the impacts of urbanization on dairy production within the RUI of an emerging megacity: the first insight from Bengaluru's case study is on the variability of emissions and by extension, the accuracy of emission computations. When computed per DPU and round, differences in round length partly explain variability of methane emissions due to EF and MMS. Nevertheless, emission variability was higher in DPS-3 and DPS-4 than in DPS-1 and DPS-2. DPS-3 and DPS-4 additionally had outliers, but not DPS-1 and DPS-2. The two biggest herds of the sample, but also one of the smallest herds, were found in DPS-3, contributing to emission variation within DPS when computed per DPU and round. Likewise, the third biggest but also some of the smallest herds of the sample were kept in DPS-4. Moreover, outliers in methane emissions due to EF in DPS-4 were not systematically from the same farm, highlighting the variability of methane emissions within the same DPU over one year. By extension, the variability in emissions also shows the sensitivity of emission computations as relatively small seasonal changes in diet or number of dairy cattle are accounted for. National emission intensities computed as per IPCC guidelines (2006) rest on estimated daily DM intake based on national dairy cattle requirements and average diet (quality). In view of the feeding inefficiencies quantified in Chapter 3 and the accuracy of emission computation, the global environmental impact of Bengaluru's DPS based on estimated DM intake would potentially differ from present computations based on quantified DM intake, including DM oversupply. This underlines once more the importance of detailed assessments of local DPS, which take advantage of local opportunities while dealing with local constraints.

The second insight from Bengaluru's case study is that, as stated above, milk CF of distinctly different DPS that co-exist within the same geographical space do differ according to their intensification level. Intensification level of Bengaluru's DPS is defined by their feeding management (Chapter 2), namely reliance on self-cultivated forages or pasture use or both. Intensification level of Bengaluru's DPS is defined, yet to a lesser extent, by their breeding management (Chapter 2), namely cattle in- and outflow within the herd and ownership of exotic genotypes. Concerning breeding, crossbreeding of local genotypes with high-yielding exotic genotypes is a common intensification strategy in tropical countries, which potentially decreases emission intensity in virtue of the general relationship between (decreasing) emission intensity and (increasing) productivity at cow-level as highlighted by Gerber et al. (2011). In the case of smallholder beef production in central Java, Indonesia, the global environmental impact of farms with crossbred animals was however similar to those with unimproved cattle: the productivity gain due to crossbreeding was offset by the additional emissions related to the additional feed resources needed to fatten the crossbreds (Widi et al., 2015). In the context of Bengaluru, no clear relationship between breeding management and emission intensity could be detected at farm-level, despite a higher share of dairy producers keeping specialized (exotic or crossbred) dairy herds in DPS-2 and DPS-4 and a positive F1 heterosis effect showing in cMO (Chapter 3). However, the in- and outflow strategy for cattle used by DPS-3 might also have contributed to the large variation in emissions per DPU and round. Concerning feeding, an effective strategy to mitigate emission intensity is high feed conversion efficiency (Hermansen and Kristensen, 2011). Keeping emission intensity in mind, the feeding management in Bengaluru's DPS can roughly be distinguish as followings: feeding little of a good quality diet and using pasture (efficient; DPS-1), feeding little of an average quality diet and using pasture (intermediate efficiency; DPS-2), or oversupplying a diet of average quality (inefficient; DPS-3 and DPS-4). This resulted in the lowest CF for the most extensive DPS, while (semi-)intensive ones (DPS-3 and DPS-4) had a higher CF. However, Bengaluru's extensive DPS-1 was extensive in its inputs of labour, land and financial resources but relied on special feedstuff and concentrate feed, which were good quality feedstuffs. Although energy and crude protein supply were variable, diet quality in DPS-1 was thus high, and overall DPS-1 had the best feed conversion efficiency of the four DPS. On the other hand, the (semi-)intensive strategies of DPS-3 and DPS-4 resulted in an oversupply of their cattle with feed, and their milk CF was thus crippled by inefficiencies, namely needless methane and nitrous oxide emissions. In DPS-2, the number of dairy cattle per herd can also partially explain the higher methane emissions per DPU and round. In opposition to the positive relationship between emission intensity and productivity highlighted by Gerber et al. (2011), in Bengaluru, the relationship between emission intensity and productivity was more complex due to the inefficiency of oversupplying cows in (semi-)intensive systems and the presence of land and labour-extensive DPS with high diet quality. In a tropical context, both Udo et al. (2016) and Bartl et al. (2011) documented a positive relationship between emission intensity and productivity at national scale. Udo et al. (2016) compared the cradle-to-farm-gate CF of three Kenyan DPS (free-grazing small-scale extensive DPS (2.6 cows in average); zero-grazing small-scale extensive DPS (1.5 cows); large intensive DPS (13.6 cows)). With all emissions allocated to milk, the small-scale extensive free-grazing DPS had the highest emission intensity (2.57 kg CO_2-eq kg^{-1} milk), the small-scale extensive zero-grazing DPS an intermediate emission intensity (2.13 kg CO_2-eq kg^{-1} milk) and the large intensive DPS the lowest (1.3 kg CO_2-eq kg^{-1} milk). Bartl et al. (2011) compared an extensive Peruvian grazing system (4.2 cows, 2.57 kg milk per cow and day) to an intensive one (5.3 cows, 19.54 kg milk per cow and day), in which cattle received maize fodder and concentrate feed. The milk CF solely due to livestock was 4.8 higher in the extensive system (11.25 kg CO_2-eq kg^{-1} milk) than in the intensive one (2.35 kg CO_2-eq kg^{-1} milk). In comparison to the CF computed for Bengaluru's DPS, the CF of both Peruvian DPS were higher. Outside of the tropics, Basset-Mens et al. (2009), however, reported a negative relationship between emission intensity and productivity for New-Zealander low input grazing DPS in comparison to more intensive DPS, which is similar to the findings in Bengaluru.

Meanwhile, Bava et al. (2014) compared three distinct DPS coexisting within the same geographical area (Northern Italy) but could not identify any intensification level performing better than the others in terms of emission intensity. Regarding spatial patterns of emission intensity, Woldegebriel et al. (2017) compared three DPS in the milkshed of Mekelle, Ethiopia. This, to our knowledge, is the only study to include DPS at distinct urbanization levels, although difference in CF is not addressed as an impact of urbanisation. The three DPS are: large scale intensive DPS, semi-intensive (peri-)urban DPS and rural DPS. CF of large scale intensive DPS was 1.60 kg CO_2-eq kg^{-1} milk, of semi-intensive (peri-)urban DPS 1.27 kg CO_2-eq kg $milk^{-1}$ and of rural DPS 0.45 kg CO_2-eq kg^{-1} milk. In Bengaluru an inverse relationship between emission intensity and urbanization level was found, since most rural and peri-urban dairy producers were (semi-)intensive, while urban dairy producers were distinctly more extensive and thus had a low CF. At last, despite distinctly different feeding management strongly affecting CF of milk, MMS of manure collected on farm was identical (solid storage) for all of Bengaluru's DPS, although later use could differ. Nitrous oxide emissions overall contributed 8% of dairy herds' total GHG emissions in Bengaluru. The benefits and feasibility of simple cost-extensive mitigation techniques such as covering heaps of solid manure with ragi straw (Forabosco et al., 2017), which is *a priori* an abundant resource in Bengaluru's RUI, should be assessed.

The third insight from Bengaluru's case study is how its dairy sector compares to international production levels and emission intensities. Irrespective of DPS, an average DPU in Bengaluru's RUI emits 1.17 kg CO_2-eq kg^{-1} ECM (cradle-to-farm-gate CF ca. 1.43 - 1.58 kg CO_2-eq kg^{-1} ECM). Annual milk offtake per cow in Bengaluru averaged 3416 ± 1533 kg ECM, which is above the 2000 kg per cow threshold characterizing low-yielding production systems with high emission intensity (Gerber et al., 2011; Gerber et al., 2013) and above the range reported for Indian crossbreed cattle by Duncan et al. (2013) and Garg et al. (2016), which underlines the high productivity of Bengaluru's dairy sector at national scale. For DPU in Western India, Garg et al. (2016) reported a lower feed conversion efficiency per cow (0.62 kg milk kg^{-1} DM) than determined for Bengaluru (between 0.71 kg ECM kg^{-1} DM in DPS-2 to 1.00 kg ECM kg^{-1} DM in DPS-1; Table 3.4) and a higher cradle-to-farm-gate CF (2.6 kg CO_2-eq per kg^{-1} milk). In Kenyan small-scale DPS, annual milk production per cow was lower than in Bengaluru, with an average of 1649 kg in free-grazing and 1950 kg in zero-grazing cows (Udo et al., 2016). In intensive large-scale systems, cows yielded 3296 kg milk $year^{-1}$, which is higher than the average annual milk production per cow in DPS-1 and DPS-2 but lower than in DPS 3 and DPS-4. CF of milk reported by Udo et al. (2016) was slightly lower in the intensive large-scale Kenyan farms (1.3 kg CO_2-eq kg^{-1} milk) than our estimate for Bengaluru, while those of the extensive small-scale DPS (2.57 and 2.13 kg CO_2-eq kg^{-1} milk) were higher. Although Bava et al. (2014) did not report annual milk production per cow for northern Italian DPS, cow productivity was high for all three intensification levels (ranging from 24.7 to 28.9 kg milk cow^{-1} day^{-1}; in average 90 cows per DPU) in comparison to Bengaluru. Despite this, the estimated cradle to farm-gate CF for Bengaluru's average DPU overlapped with the higher range of the Italian systems (0.90 to 1.56 of CO_2-eq kg^{-1} milk), underlying that small-scale tropical DPU can be equally emission-efficient to large-scale highly-productive DPU in Western countries.

4.5 Conclusions

Bengaluru's case study sheds light on dairy production within an urbanizing environment leading to DPS with distinctly different environmental impact according to the intensity level of their feeding management. In line with the previously assessed feed conversion efficiency, Bengaluru's extensive dairy farms had a lower CF of milk since their feeding management was the most efficient. In opposition, (semi-)intensive production systems oversupplied their cattle with feedstuffs and nutrients in relation to milk yield, which crippled their CF. With millions of small-scale dairy producers in India and beyond, this study highlights the importance of a judicious local assessment of system-specific GHG emissions to assess their global environmental impact. Indeed, local production strategies are based on a complex set of opportunities and constraints and local specificities such as the reliance on organic wastes as feeds can positively contribute to more sustainable dairy production systems. The local perspective therefore also challenges the definition of what is an extensive or an intensive system, especially in terms of resources use efficiency and global environmental impact.

General discussion

5.1 Methodological considerations

5.1.1 The definition of urbanization

A household survey is a cost-efficient method to collect a large number of data provided the selection of a representative sample (Fraval et al., 2019). Our research area and sampling process was established by the research unit FOR2432 and the SSI by Hoffmann et al. (2017) was used as proxy for the urbanization level of each settlement. The SSI was a practical approach to the complex definition of urbanization, which allowed for a characterization of urbanization levels and for the subsequent household survey at the scale of a megacity's RUI. At transect level, the number of dairy producers in Nsect and Ssect was balanced and the spatial pattern showed no bias despite different selection thresholds. At settlement level, the number of dairy producers correlated to SSI and was used as a predictor to reveal spatial patterns of Bengaluru's DPS but did not show a bias in their selection. The use of vaccination lists was a satisfactory way to randomly select dairy producers at settlement level and could easily be matched with scouting the settlement on foot and talking to local inhabitants in the few settlements where no such list existed.

In a developing country, another way to look at urbanization could have been through the lens of market integration, namely the access to inputs and marketing channels, and indirectly of road network. As dichotomized producers and consumers are linked through the transport of agricultural goods (Butler, 2012; Lamine, 2015; Steel, 2008), the density and quality of the road network can be an important predictor of market integration (Dudwick et al., 2011; Tacoli, 2003; Thapa and Murayama, 2008) and indirectly of urbanization when defined as market integration. An example is Lucknow, India, where a clear link between urbanization level and road network has been established (Shukla and Jain, 2019). The quantification of the density and quality of the road network is however a complex task and challenges a monocentric approach to urbanization as it focuses on the accessibility of rural populations to goods and services, often provided by urban areas of different size and accessibility (Tacoli, 2003). In the case of dairy production in Bengaluru's RUI, the centred SSI approach to urbanization, namely the use of the settlement's distance to the city centre as one important parameter of the index, was coherent, since the network of dairy cooperatives in Bengaluru's RUI was also centralized through KMF. When looking through the lens of market integration, Bengaluru's urban areas could have been defined as areas where dairy producers had market access but were not integrated in formal value chains, while rural dairy producers were those who were integrated only through dairy cooperatives. Peri-urban areas are often theorised as mixed spaces, where sectorial interaction and linkages are the most intensive (Lerner and Eakin, 2011; Tacoli, 2003, 1998), but in our research they did not stand out as very different from rural areas. Through the lens of market integration, peri-urban spaces could thus have been defined as mixed spaces where dairy producers were integrated both through dairy cooperatives and in a decentralized informal way, i.e. where the market integration was the most intense and diverse. A fourth level of urbanization could have been defined as *remote rural* areas, where dairy producers were not integrated in the market, with access neither to inputs nor to consumers. In our sample, two settlements (Chikka Muddenahalli at the upper border of Nsect and Muninagara close to the eastern border of Ssect) were rural and only had access to a dairy cooperative in a close-by settlement. Low market integration showed in the fact that dairy producers in both settlements tended to keep more native cattle (crossbreeds) and more milk for HH consumption than in other settlements. When specifically categorized as an urbanization level and selected in higher numbers, such remote rural settlement could have offered an interesting contrast to settlements which were also rural but already impacted by urbanization when considered through the lens of market integration, which challenges our definition of rurality and the dichotomization of rural and urban areas when those are linked with and impact each other. An approach to urbanization through the lens of market integration in the context of Bengaluru's RUI would have however been specific to dairy production; it would have required a higher amount of preliminary work and led to a more fragmented urbanization pattern.

5.1.2 Dairy production baseline survey

To be a cost-efficient method to collect a large number of data, a household survey must also implement a robust collection protocol to guarantee data quality, namely credibility (observations lie within a plausible range) and consistency (observations are accurate; typically assessed over repeated rounds of data collection; Fraval et al., 2019). Characteristics of our dairy production baseline protocol and survey such as beforehand training of enumerators, shortness and generality of questions, and completion of each survey by a team of one enumerator and one researcher guaranteed a minimum quality. When possible, to ease the understanding between the dairy producer, the enumerator and the researcher, we asked to see the cattle, thus checking some baseline information regarding the herd against the "truth" (Fraval et al., 2019). The homogeneity of the collected data across all surveys speaks for a high credibility. With only one round of data collection however, data consistency could not be assed and when dubious, which was mitigated by stepping back in the level of detail: e.g., the characterization of the cattle genotype by the dairy producer was not very reliant within and across herds as cattle were sometimes multi-generation crossbreeds without genetic records or as dairy producers often mentioned the genotype of the cow without accounting for the one of the bull, an inaccuracy often noticed when we asked to see the cattle. Thus, inconsistency in genotype characterization was mitigated by using broad genotype classes. The broad approach of our dairy production baseline survey also proved useful in retrospective regarding e.g. pasturing and reliance on self-cultivated forages: first, because those parameters were later quantified in detail, making more consistent data automatically available. Second, because the detailed quantification of those parameters also showed their variably within farms without calling into question the consistency of the baseline data as they were broader; for example, only a part of the herd was going to pasture or cattle from a same herd spent different amounts of time on pasture across seasons. This also underlines the complementarity of both a large qualitative and small quantitative data collection to form a coherent overall database.

5.1.3 Quantification of feed conversion efficiency and carbon footprint

Specific methodological considerations regarding the quantification of feed conversion efficiency (Chapter 3) and carbon footprint (Chapter 4) have already been highlighted in the respective chapters. Overall, the monitoring of dairy cattle nutrition for one year and across 28 DPU was labour and time intensive. The number of observations for carbon footprint calculations was thus limited since data are usually computed at farm-level. This limitation was partly mitigated by computing them at farm-level per monitoring round rather than for the whole year. As CF is a ratio, comparison between DPS based on emission intensity per round was not a problem, although the average yearly CF was used for international comparisons as per IPCC guidelines (2006). The number of observations was not a problem for feed conversion efficiency calculation since data were computed at cow-level. Both quantifications showed significant differences between DPS, highlighting the diversity of DPS coexisting within a same rural-urban interface and the importance of regional assessments. Our detailed monitoring of dairy cattle nutrition in the context of urbanizing India on non-experimental farms added valuable insights to our baseline dairy production survey and proved to be a coherent work and a robust base for further research on Indian dairy production systems in an urbanizing environment.

5.2 A critical perspective on Bengaluru's dairy sector

Our research showed the coexistence of four DPS within Bengaluru's RUI with distinct dairy production strategies, which resulted in differences in intensification level, feed conversion efficiency and carbon footprint. While each research chapter provides interesting insights on the impacts of urbanization on DPS within Bengaluru's RUI, altogether they also provide interesting insights on agricultural transition in and commercialization of the dairy sector of an emerging megacity in India.

5.2.1 Agricultural transition

Shift in the supply side. Urbanization created a shift in the supply side of Bengaluru's dairy sector, namely the production of milk, by affecting the availability of land and labour. Concerning land, land holding per agricultural HH in and around Bengaluru is typically small (85% own less than 2 ha; World Bank, Urban Development and Resilience Unit, 2013). Although labour-intensive, Indian dairy production has a development potential that is not overly land-intensive (Janssen and Swinnen, 2019). Bengaluru's "landless" dairy producers (DPS-1) decreased the use of private land to a maximum by not cultivating forages or even not owning land at all, showing the independence of dairy production from the availability of land as a private resource to an unexpected extend: on one hand, because some dairy producers were indeed completely independent from land, even public spaces. On the other hand, because rural - and not only urban or peri-urban - dairy producers also adopted this land-extensive production strategy, while elsewhere access to resources such as land is critical to rural livelihoods (Bah et al., 2003) and the most direct impact of urbanization is the decrease of land availability in (peri-)urban areas (Satterthwaite et al., 2010). In Cairo, Egypt, "landless" (peri-)urban DPS are also reported by Daburon et al. (2017) but they are completely indoors as dairy animals are not allowed to pasture in the streets. "Landless" dairy producers were however a minority among Bengaluru's dairy producers (21%) underlining that such extensive production strategy evolved from a specific set of constraints and opportunities.

Most of Bengaluru's dairy producers had a land-based approach to dairy production and despite urbanization, their activity was not constrained by land availability in the immediate future: land owned by dairy HH was typically inherited, which guaranteed land ownership despite rising land prices (Sudhira et al., 2007). However, decreasing land availability potentially increases opportunity costs of not selling the land, especially around major transport axes between Bengaluru and neighbouring smaller cities, and in peri-urban areas (Shukla and Jain, 2019; Sudhira et al., 2007; Verma et al., 2017). Additionally, decreased land availability is a potential constraint for low-income HH without inherited land, who would like to start (semi-)intensive dairy production (Bah et al., 2003), or dairy HH, who would like to expand their (semi-)intensive dairy production to a larger scale.

Concerning labour, as previously highlighted (Chapter 2), available family labour and dairy production were closely linked. Irrespective of DPS, Bengaluru's urban dairy producers had significantly larger herds than those in rural and peri-urban areas; having access to plenty of feed resources, their labour disinvestment in forages cultivation was potentially traded-off for the maintenance of a larger herd or an off-farm activity or both. The socio-economic data collected point at urbanization potentially already impacting availability of family labour by increasing financial and physical opportunity costs of on-farm labour, especially of the younger, better educated generation (Satterthwaite et al., 2010). In contrast to Nakuru, Kenya, family labour in Bengaluru was not traded-off for hired labour (Migose et al., 2018). This might be due to non-attractive working conditions for day-labourers or low availability of hired labour, as resources access was sufficient for rural labour to have their own activity (Bah et al., 2003; Satterthwaite et al., 2010; Tacoli, 2003). Thus, as already underlined (Chapter 2), financial and physical attractiveness of off-farm jobs in Bengaluru might partly explain the lower number of dairy producers in urban areas and challenges the long-term persistence of dairy production in and around Bengaluru (Inwood and Sharp, 2012).

Shift in the demand side. Despite not being the focus of our research, no data from the supply side indicated that the demand for milk was problematic: dairy producers strived for higher milk offtake per cow, dairy cooperatives bought all available milk and informal marketing channels were financially rewarding. With an ever growing population (Kumar et al., 2016), strong socio-cultural norms regarding vegetarian diets and status of the cow (Cunningham, 2009; Kennedy et al., 2018) as well as preference of raw fresh milk (Lapar et al., 2010), the demand for milk in Bengaluru is huge. Lapar et al. (2010) additionally reported that in the state of Assam, India, urban consumers readily spent money on high-value dairy products. Urbanization is usually associated with a shift in diet preferences (Regmi and Dyck, 2001). In the case of Bengaluru, Erler and Dittrich (2017) reported a complex coexistence of on-going food transitions, including a return to the traditional diet, in which dairy has a central part. The decades-long existence of a large dairying community in 20th century urban

Singapore largely linked to and supplying Singapore's Indian community is a good example of how strong the demand for milk in the Indian society is (Wikkramatileke and Singh, 1969).

Intensification versus extensification. At farm-level, production inputs are easily available through dairy cooperatives, especially concentrate feed and exotic genotypes. The use of inputs and strive for higher daily milk offtake was common in all DPS and indicated an overall intensification trend in Bengaluru's dairy sector (Alderman, 1987; Cunningham, 2009; Hemme et al., 2003). Intensification lead to higher MO per cow and day but DPU were crippled by inefficiencies especially due to the oversupply of LDH with feed in (semi-)intensive DPS and of dry cows and heifers in general. Thus, despite Bengaluru's dairy sector starting to intensify, there is a real need to fine-tune the use of production inputs toward efficiency and to bring about a substantial increase in MO. Moreover, this intensification trend has a limited range: dairy producers made use of easily available inputs but did not make consequent long-term investments into the welfare of their cattle, the scaling-up of their dairy production or the persistence of their DPU. Financial capital investment was limited to rare production (e.g., buying a chaff cutter) or husbandry (rubber matt) improvements, both potentially subsidised through dairy cooperatives, whereas no investment aimed at increasing herd size, e.g. by hiring labour or mechanize the laborious tasks (e.g., milking machine).

Diversification versus specialization. A trend toward production specialization was seen at farm-level given the focus on dairy production as a market-oriented activity: ownership of additional livestock was low in comparison to (peri-)urban HH in West Africa (Amadou et al., 2015; Roessler et al., 2016). The trend toward specialization in dairy production can be linked to the high share of vegetarians in India (Government of India, 2014) and their focus on dairy products as source of animal protein, as a typical consumer-to-producer feedback on produced goods and services (Sundkvist et al., 2005). Three quarters of the dairy producers coupled dairy production and crop production, but crop cultivation was mostly for HH consumption or for both HH consumption and sale, and seldom exclusively for sale. A trend toward occupation and income diversification was however seen at HH level with half of all HH having one or more HH members, especially of the younger generation, working off-farm and most HH having a mixed income. At Bengaluru's RUI scale, there was thus a potentially stronger trend toward diversification as off-farm opportunities gain in attractivity, which could affect the persistency of smallholder dairy production as it is linked to internal HH dynamics (Inwood and Sharp, 2012).

5.2.2 Market integration

As described by Lobao and Meyer (2001), US farming saw a major agricultural transition in the 20th century when family-farming became no more viable and agriculture an industry. The structure of the US dairy sector hence changed from numerous family DPU to less numerous and much larger DPU. This shift has not yet happened in Bengaluru's RUI as dairy production is still a family-business, which can (partly) sustain a family. In contrast to the US, the urbanization of Bengaluru's RUI seems to pull people out of dairy production (opportunity cost of selling land; attractivity of off-farm employment) rather than pushing them out.

When looking at our results, however, one might ask whether there is any commercial dairy production in Bengaluru's RUI. Regarding large-scale commercial DPU, insights gained from one purposefully conducted baseline dairy production survey on large scale commercial buffalo DPU (50+ buffalo) located close to a rural settlement but not included in the analysis showed that such large-scale commercial farming does exist but might not be settlement-based and have its own formal marketing channel(s) (in this case direct delivery to an ice-cream processing plant) rather than relying on a dairy cooperative. Within our sample, larger herds were often kept by joint families (more than one sibling and their families living in a common household), giving them access to more family labour and financial capital (Figure 5.1). The structure of the Indian dairy sector at national level (smallholders with two to five cows still produce 80% of the national milk volume; Cunningham, 2009; Figure 5.2) confirms that the number of large DPU is marginal and not representative at the scale of Bengaluru's RUI.

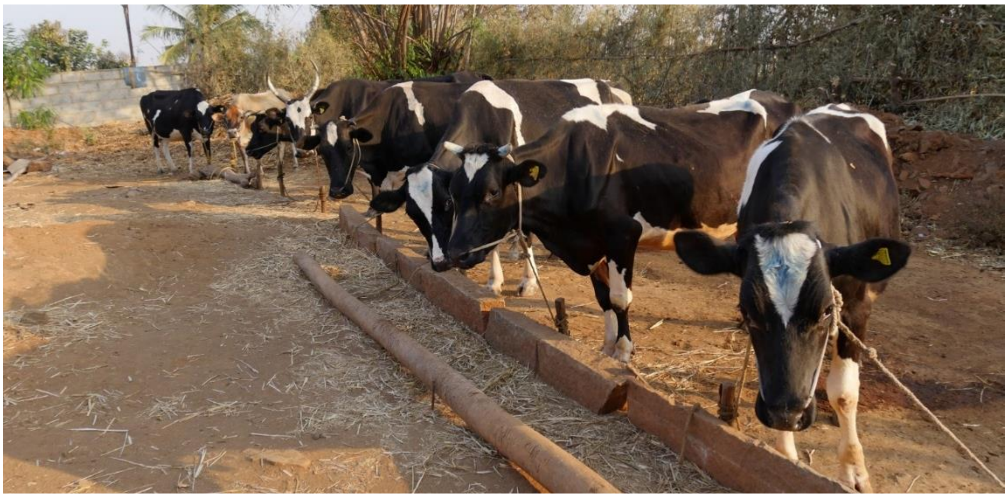

Figure 5.1 A large herd by Bengaluru's standards: seven cows and one heifer, kept by a joint family.

Figure 5.2 A smaller herd (two cows and two heifers), more typical of Bengaluru’s dairy sector.

The role of dairy cooperatives. Nevertheless, commercial agriculture is not linked solely to large numbers of animals but rather to the integration of dairy producers into the formal market, which in rural and peri-urban areas was assured through dairy cooperatives. In rural areas, the supply of milk was higher than the demand and delivery of milk to a dairy cooperative the only way for smallholders to reach a larger number of consumers. Market integration of smallholders was already a success of Operation Flood (Cunningham, 2009) and continues to be as the network of dairy cooperatives expands. The benefits of market integration through dairy cooperatives are huge both in terms of production, as seen in Ethiopia (Chagwiza et al., 2016) but also in terms of sustaining livelihoods. By subsidizing inputs and output, dairy cooperatives also maintain the possibility of dairy production as a livelihood and to mitigate push-out factors such as lack of rentability.

Market integration and resilience. It is interesting to consider Bengaluru’ DPS through the lens of SES and their capacity of resilience. In this perspective, DPS-1 can be interpreted as the transformation of traditional rural DPU into a complex, more resilient, social-ecological system under the pressure of urbanization. Yet, the SES of DPS-1 is different for urban DPU and rural and peri-urban DPU, and must be compared to the SES of (semi-)intensive rural DPS.

First, at the core of all SES are the dairy producers, their family and their dairy herd. The viability of these SES can be measured as a positive contribution of dairy production to the food security of the HH and a reasonable net income for the family labour invested in dairy production (Grafton et al., 2019; Termeer et al., 2019). In context of an urbanizing environment, the definition of what is a *reasonable* net income is challenged by the economic attractiveness of off-farm activities. Dairy producers are tightly linked to their dairy herd, even spatially, as cows are often kept under the same roof even in urban areas, as also reported for Cairo, Egypt (Daburon et al., 2017). In exchange for daily labour investment, cows provide milk to the dairy producers, which contributes to HH food security, income, but also employment and the preservation of their socio-cultural identity (Lerner and Eakin, 2011; Tacoli, 1998). Consumers constitute a secondary core of these SES, linked to dairy producers by a strong (daily) flow of agricultural goods, mainly (raw fresh) milk but in urban areas also socio-cultural services, in exchange for a financial flow. In the background of these SES are the city, the ecosystem and the institutions related to Bengaluru's dairy sector, namely KMF and the dairy cooperatives.

The characteristic of the urban SES is that it allows the integration of dairy producers within the city through their activity, where they and their families can benefit from good infrastructure (schools and hospital) while pursuing their economic activity and preserving their cultural identity. The city provides the dairy producers with a large pool of directly reachable consumers, public grounds for pasturing and forage collection (Figure 5.3), and additional forage sources in form of organic wastes. In turn the city benefits from the recycling of (feedable) organic waste through cows and the daily provision of a high-value but perishable product. All these linkages and multiplies services between the SES components constitute a robust SES with a tight feedback loop between consumers and dairy producers that consumers trust (Lapar et al., 2010). Market integration usually means that producers become susceptible to price volatility of in- and outputs. Yet, the extensive management in DPS-1 greatly reduces the susceptibility of dairy producers to price volatility as they spent limited financial capital on inputs and the demand for milk is unlimited and financially rewarding. Especially extensive urban dairy producers are very adaptive as they feed their cows from a large range of feedstuff and take advantage of unconventional feed sources such as market wastes. Moreover, if their output varies or they don't sell all their milk to their direct customers, they can fall back on a dairy cooperative to sell their production. The sub-capacity of resilience, transformability, can easily be seen from the nature of this extensive DPS, especially its urban DPU, which transformed their dairy farm in response to the urbanization of their immediate environment without losing their socio-cultural identity. It is important to highlight that the urban dairy producers were neither newcomers to the city of Bengaluru nor new dairy producers. Rather, the city came to them at an exponential speed, engulfing their farm within a few decades, as seen in 19th century London (Atkins, 1977).

Figure 5.3 Despite its 10 million inhabitants, not all of Bengaluru is built-up, as here 10 km from the city centre, and offers public grounds suitable for pasture and forage collection.

However, since it is operating in built-up areas, urban dairy production has potentially negative ecological consequences especially when crop and dairy production are decoupled: on one hand, wasting and accumulation of nutrients (in feed leftovers and excrements) in the city, which is transforming Bengaluru into a nutrient sink, as has also been reported for African cities (Drechsel and Kunze, 2001; Schlecht et al., 2019). On the other hand, Bengaluru's water bodies are polluted through manure mismanagement (excessive flushing away of cattle excrements). Neither dairy producers nor consumers seem to be aware of these environmental problems. Because of the delay in negative environmental responses (e.g., drinking water with high nitrate concentration of faecal coliforms) and their potentially large scale, these problems will be difficult to tackle without the intervention of Bengaluru's institutions. Additionally, tight cohabitation between humans and animals also represents a health hazard (Butler, 2012; Daburon et al., 2017) but concerns over health risk associated with urban cattle husbandry do not seems to go further than a general expectation of maintaining a clean cowshed. As detailed in Termeer et al. (2019), information disconnect about negative environmental or health effects appear to strengthen robustness, thus short-term resilience of the SES, but undermine the adaptability and transformability that guarantee long-term resilience of the SES. Thus, to enhance long-term resilience of urban DPU, Bengaluru city authorities must regulate manure management in urban areas (e.g. in assessing the feasibility of coupling of urban "landless" DPU with agricultural production elsewhere in Bengaluru's RUI as suggested in Chapter 3) and implement standards for urban cattle husbandry and eventually subsidize necessary improvements. Additionally, the involvement of Bengaluru city authorities in urban dairy production and establishment of standards would allow the recognition of urban dairy production and potentially improve the livelihood of urban dairy producers and their families.

In contrast, (semi-)intensive rural DPU completely relied on dairy cooperatives for their inputs and for the commercialization of their output. Market integration through dairy cooperatives is a successful approach to improvement of rural livelihood, enhancing participation of small-scale dairy producers in the development of dairy production (Cunningham, 2009; Wouters and van der Lee, 2010). Rural DPU however typically suffer from the traditional spatial and sectorial dichotomization of rural and urban areas, which could potentially lead to overexploitation of local resources: land and water to produce crops, vegetables and fodder for cattle, which are mostly exported as nutrients and virtual water to the city, thus potentially decreasing soil fertility and local water resources. This red-loop trap may develop as urban demand continues to increase; it might entail environmental injustice between urban consumers and rural (dairy) producers as only the latter will have to bear negative environmental consequences (poor soils, overexploited ecosystem), whereas the only advantage of their proximity to the city is the financial reward of their economic activity.

5.3 Generalization of results and further research

Despite the specific context of India, our research provided insights into livestock production systems in an urbanizing environment that can be generalised: the socio-cultural importance of the cow is indeed strong and must be accounted for in the analysis of the Indian dairy sector. Importance for the livelihood and multiple values, including socio-cultural, of cows and livestock in general, are however not limited to India and have been reported from other countries in the Global South such as Kenya (Weiler et al., 2014), even if expressed in less obvious ways. Irrespective of the attribution of socio-cultural values to livestock, demand for milk is affected by socio-cultural behaviours such as fasting practices of Orthodox Christians in Ethiopia (D'Haene et al., 2019). Operation Flood shaped today's Indian dairy sector and the role of dairy cooperatives as tool of market integration is another aspect of our research that is also found e.g. in Ethiopia (Chagwiza et al., 2016) and offers an interesting development perspective to urbanization hotspots where formal market integration is lacking, as e.g. in Cairo, Egypt (Daburon et al., 2017).

This research, especially its limitations, thus constitutes a solid basis for further research on the impact of urbanization on livestock production systems in India and other urbanization hotspots in the Global South. To further understand the current impacts of urbanization on livestock production systems but also predict and support further development of livestock production systems, the following aspects should be researched:

Because Inwood and Sharp (2012) showed that family farms with a heir in perspective will develop strategies to persist in an urbanizing environment, future research on livestock production systems in an urbanizing environment should focus on internal family dynamics, namely the availability of family labour, the possibility to hire labour and the link between labour input and productivity at herd level. In addition to gain a detailed understanding of processes at farm-level, future research should also focus on identifying the SES in which livestock production units are embedded, because the frameworks of SES and resilience through social-ecological linkages casts a new understanding on system transformation at sector level in an urbanizing environment. From this perspective, the linkages and feedbacks between producers and consumers are of major importance. Thus, future research should focus on analysing production and consumption as two sides of the same problem, e.g. unsustainable resource use or health risk as with the *One Health* framework, rather than depicting them as distinct fields of research.

Since the present study analysed the current status of Bengaluru's dairy sector, it provides few insights on how it might further evolve. One way to overcome this limitation would be collecting data on HH previously involved in dairy production and their reasons for stopping their activity, thus increasing the understanding of the constraints and opportunities that urbanization offers, especially regarding access to essential agricultural resources. Anticipating the future developments of Bengaluru's dairy sector is important for institutions and policy makers to reasonably shape the processes while supporting its diversity, but also because ongoing urbanization processes in West Africa and Asia offer a unique opportunity to rethink food systems and rural-urban linkages. Should production and consumption be dichotomized on a spatial and sectorial basis? How to foster fair and good quality rural-urban linkages? Which place do peri-urban spaces occupy in the food supply strategy of emerging megacities? Do extensive but highly adaptable production systems have a future in an urbanizing environment, as they rely on locally available resources, opportunities and constraints? Should small-scale family farming be preserved rather than transformed into large-scale commercial production? And is small-scale family-farming *versus* large-scale commercial production even mutually exclusive?

5.4 Conclusions

This study showed that the impacts of urbanization on livestock production systems are complex and need to be studied to overcome simplistic assumptions on the mechanisms of urbanization, notably those of dichotomizing rural and urban areas on a spatial and sectorial basis and especially in the Global South. Understanding and quantifying on-farm mechanisms and transitions are important but only embedding them in their larger social-ecological context and understanding the links between social-ecological components will allow building sustainable and resilient food systems in an urbanizing environment.

In western countries, urbanization has led to spatial and sectorial dichotomization of rural and urban areas and the shift from family agriculture to large scale commercial agro-enterprises. In the rapidly urbanizing areas of West Africa and Asia, however, urbanization might lead to different outcomes. Africa and Asia are faced with the complex task of reinforcing their agriculture in a sustainable and resilient way to respond to the growing demand for agricultural commodities but also to the growing threat of climate change, while keeping the numerous smallholders currently active in agriculture at the centre of their development strategies. By improving understanding of agricultural transitions in the case of dairy production in an urbanizing environment, the present study can support the implementation of future dairy development programs by pointing to local constraints and opportunities and the importance of several social-ecological components that should all be considered in such initiatives.

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Did you ever see a cow in the middle of the street?

In Bengaluru, India, it is a common sight despite Bengaluru being one of the fastest urbanizing city in the world, with now over 10 million inhabitants. In short, the present work aims to explain how and why a cow in the middle of the street is a common sight in Bengaluru.

In full, the present work aims to provide deeper insights into the impacts of urbanization on dairy production, taking the dairy sector of the emerging megacity of Bengaluru as case study. The present work first focusses on identifying and characterizing the dairy production systems that co-exist in the rural-urban interface of Bengaluru, while highlighting potential linkages between its social-ecological components. In a second step, the present work focusses on quantifying the impacts of distinct dairy production strategies in terms of resources use efficiency, namely feed conversion efficiency, and global environmental impact, namely emission intensity of greenhouse gasses, in relation to the spatial distribution of Bengaluru's dairy production systems across its rural-urban interface.

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