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York, L., Heffernan, C. and Rymer, C. ORCID:
<https://orcid.org/0000-0002-3535-4330> (2017) A comparison of policies to reduce the methane emission intensity of smallholder dairy production in India. *Agriculture, Ecosystems and Environment*, 246. pp. 78-85. ISSN 0167-8809 doi:
<https://doi.org/10.1016/j.agee.2017.05.032> Available at
<https://centaur.reading.ac.uk/70792/>

It is advisable to refer to the publisher's version if you intend to cite from the work. See [Guidance on citing](#).

To link to this article DOI: <http://dx.doi.org/10.1016/j.agee.2017.05.032>

Publisher: Elsevier

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1 **A comparison of policies to reduce the methane emission intensity of smallholder dairy**
2 **production in India.**

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12 **Abstract**

13 Within the dairy sector, the effects of climate change are particularly diverse as cows are
14 affected by, and a significant contributor to climate change. With a burgeoning body of work
15 indicating the importance of livestock's contribution to climate change (via Greenhouse Gas
16 (GHG) emissions), the dairy sector will increasingly be targeted for emission reduction. Yet,
17 gaps in knowledge remain as to the effectiveness of interventions in achieving emission
18 reductions. The investigation examines two high-profile Indian policies to evaluate their
19 effectiveness in reducing the methane emission intensity of milk production in Odisha, India.
20 Selected policies included the installation of smallscale anaerobic digesters and the control of
21 Foot and Mouth Disease (FMD). The interventions were evaluated at the cow level informed
22 by data collected from 115 smallholder dairy producers in Puri (n=31) and Khurda (n=84)
23 districts in Odisha, India. The installation of an anaerobic digester was found to increase
24 methane emission intensity by 4.41-5.01%. Control of FMD reduced methane emission
25 intensity by 3.68-12.95% depending on the infection scenario considered. The findings
26 highlight the importance of contextually relevant and multi-sectoral approaches to mitigation
27 as the increase in methane emission intensity following anaerobic digester installation
28 represents movement of emissions from the energy sector into the dairy sector where
29 mitigation is inherently more complex. Thus, the long-term usefulness of anaerobic digester
30 installation as a mitigation strategy is limited.

31 Keywords: Climate change, India, Odisha, anaerobic digester, Foot and Mouth Disease.

32 **1. Introduction**

33 The livestock sector is a key feature of the Indian economy contributing approximately 4.1%
34 to GDP in 2012-2013 (Government of India, 2014a). The dairy sector is the most important
35 component of the Indian livestock sector contributing 65.1% of the total value (Government
36 of India, 2014b). The Indian dairy sector is the largest in the world composed of
37 approximately 44.5 million milking cows (Government of India, 2014b) representing 16.7%
38 of the world's dairy cattle population (FAO, 2013).

39 The Indian dairy sector is primarily composed of smallholders who are responsible for 70% of
40 India's bovine (cattle and buffalo) population (Datta *et al.*, 2015). Within India, smallholder
41 operations are characterized by small landholdings (< 2 ha) and small herd sizes (an average
42 of 0.89 female cattle per household) of low productivity (Datta *et al.*, 2015). The average
43 daily milk production of India's crossbred cows is 7.0 kg/cow and 2.4 kg/cow for indigenous
44 cows (Government of India, 2014b). However, a great deal of variability is noted between
45 states. For example, Odisha has lower average levels of milk production at 6.2 kg/cow per day
46 for crossbred and 1.5 kg/cow per day for indigenous cows (Government of India, 2014b).

47 Due to constraints associated with feeding, breeding, health and management (Government of
48 India, 2012b) the low levels of milk production make the Indian dairy sector one of the most
49 greenhouse gas (GHG) emission intensive (Gerber *et al.*, 2011). Indian estimates of emission
50 intensity (see Swamy and Bhattacharya, 2006; Jha *et al.*, 2011; Patra, 2012) are considered
51 partial estimates as they are not weighted to consider the associated dairy population (such as;
52 replacement heifers, cull calves, etc.) and focus heavily on methane (CH₄) emission from
53 enteric fermentation and manure management practices. Nitrous oxide emissions receive little
54 attention due to their limited importance within the smallholder sector (Swamy and
55 Bhattacharya, 2006; Patra, 2012). Similarly, carbon dioxide produced during respiration is
56 excluded as this represents the return of photosynthesized carbon dioxide to the atmosphere
57 and does not affect net carbon dioxide emissions from livestock (IPCC, 2006a). Indeed,
58 emission inventories from India's National Communications to the United Nations
59 Framework Convention on Climate Change (UNFCCC) are considered complete emission
60 estimates (see Government of India, 2004, 2012a). However, these reports do not consider
61 the emission intensity of milk production.

62

63 Indian crossbred dairy cows are estimated to produce between 0.53 and 0.70 kg CO₂
64 equivalents/kg of milk (Swamy and Bhattacharya, 2006; Jha *et al.*, 2011). Indigenous Indian
65 cattle have a higher methane emission intensity producing between 1.03 and 2.40 kg CO₂
66 equivalents/kg of milk (Swamy and Bhattacharya, 2006; Jha *et al.*, 2011). In terms of Fat and
67 Protein Corrected Milk (FPCM), the emission intensity of indigenous and crossbred milk
68 production was found to 6.5 kg CO₂ equivalents/kg of FPCM milk and 1.4 kg CO₂
69 equivalents/kg of FPCM milk, respectively (Patra, 2012). Although the value offered by Patra
70 (2012) is a more complete estimate of emission intensity as it is weighted to consider the
71 associated dairy population, the author includes all cattle (including draft animals) within the
72 dairy sector. In doing so, the emission intensity offered is likely to be an overestimation.

73

74 Indian estimates of emission intensity appear comparable to the emission intensity estimates
75 from northern production systems. For example, in the United states Capper *et al.*, (2009)
76 found an emission intensity of 1.35 kg CO₂ equivalents/kg of milk for modern (year 2007)
77 intensive methods of production. Similarly, in the United Kingdom Foster *et al.*, (2007) found
78 emission intensity to be 1.14 CO₂ equivalents/kg of milk. However, these authors employed a
79 Life Cycle Assessment (LCA) approach which is common practice for dairy sector emission
80 estimates in the global north (see FAO, 2010; Kristensen *et al.*, 2011; Opio *et al.*, 2013). The
81 LCA approach provides a more comprehensive estimate of emission intensity as the
82 emissions associated with feed production and processing are included (in addition to enteric
83 and manure management sources) (FAO, 2010). Thus, it is likely that the emission intensity
84 of Indian milk production will be significantly larger should a LCA approach be used. Using
85 a LCA approach, Gerber *et al.*, (2013) estimated the average emission intensity of South
86 Asian integrated crop-livestock systems to be 5.5 kg CO₂ equivalents/kg of milk. The global
87 average was found to be 2.7 kg CO₂ equivalents/kg of milk (Gerber *et al.*, 2013).

88

89 It is inevitable that the Indian dairy sector will be targeted for GHG emission reduction due to
90 the high emission intensity and sheer size of the sector. However, achieving emission
91 reductions from the Indian dairy sector is inherently complex due to the contributions
92 livestock make to the country's economy and food security. As such, India is currently
93 without any dairy sector GHG emission mitigation policies. Yet, the Indian government
94 policy position can be gleaned from existing documents which indicate emission reductions
95 must be achieved without reducing productivity or dairy cattle population size (Government
96 of India, 2011b).

97

98 Internationally, authors have begun to question whether reductions in GHG emission can be
99 achieved without a reduction in livestock population. For example, Webb *et al.*, (2014) found
100 that achieving a 20% reduction in UK livestock sector GHG emissions was not possible
101 without reducing output (or exporting emissions overseas). Similarly, reduced stocking rates
102 were required to reduce emissions from the New Zealand dairy sector (Adler *et al.*, 2013;
103 Doole, 2014). Thus, achieving emission reductions without reducing the national herd size
104 represents a significant challenge. Indeed, the development of a low emission dairy sector
105 under the guise of sustainable intensification may be possible (Gerber *et al.*, 2011, 2013;
106 Herrero *et al.*, 2015). However, intensification is particularly challenging within India due to
107 chronic feed shortages (Government of India, 2012b, 2013). As such, questions remain as to
108 whether emission intensity can be reduced to the level required to offset the increases in
109 emission expected in response to increasing demand (Delgado *et al.*, 1999; Pica-Ciamarra and
110 Otte, 2009).

111

112 A range of existing Indian policies are likely to have an impact on the GHG emission
113 intensity of the dairy sector. In this circumstance, policymakers could reconsider existing
114 policies within an overarching climate change framework. For example, over the past 30
115 years, the installation of smallscale anaerobic digesters has been a government priority. By
116 the end of 2017, 5.6 million smallscale anaerobic digesters will have been installed with over
117 6.5 million installations expected by 2022 (Government of India, 2011c). However, the effect
118 of anaerobic digesters on dairy sector GHG emissions is largely unknown as the energy sector
119 has been the focus of research. As a result, no studies have been undertaken to evaluate the
120 impact of anaerobic digesters on dairy sector emissions, despite system leakage being
121 identified as a potential concern (e.g. Bruun *et al.*, 2014).

122 Disease control is a stand-alone priority within Indian livestock policy (Government of India,
123 2013). From a mitigation perspective, disease control provides significant co-benefits as
124 improved productivity (and reduced cull rates) will reduce GHG emissions (Hospido and
125 Sonesson, 2005). Foot and Mouth Disease (FMD) could be targeted as significant resources
126 have been allocated to its control. During 2013-2014, the Indian government spent Rs. 2.5
127 billion on FMD control (Government of India, 2014b). It is estimated that the Indian bovine
128 (cattle and buffalo) population receive 150 million doses of FMD vaccination annually
129 (Knight-Jones and Rushton, 2013). Despite such investments India has the world's highest

130 incidence rate (along with China) at 3.39% (Knight-Jones and Rushton, 2013). During 2013,
131 it is estimated that 75 255 bovines (including cattle and buffalo) were affected by the disease,
132 resulting in the death of 7 736 individuals (Government of India, 2014b). However, such
133 infection levels likely underestimate the importance of the disease. For example, at a
134 prevalence of 3.39% (Knight-Jones and Rushton, 2013) assuming a herd size of 44.5 million
135 (Government of India, 2014b) it would be expected that approximately 1.5 million dairy cows
136 would be affected (assuming no vaccination program is in place). Such a figure is more
137 commensurate to the annual median cost of production losses (i.e. Rs. 126 billion (Knight-
138 Jones and Rushton, 2013)).

139 Therefore, the aim of the investigation was to compare two policies to determine their
140 effectiveness in reducing the GHG emission intensity of milk production in Odisha, India.
141 The installation of smallscale anaerobic digesters and the control of FMD in dairy cattle were
142 selected due to their high profile and importance within Indian livestock policy. Indeed, a
143 range of Indian policies will also affect the emission intensity of milk production. However,
144 the selected policies were locally relevant and had been implemented widely throughout the
145 research sites. The interventions were evaluated at the herd level informed by data collected
146 from 115 smallholder dairy producers in Puri (n=31) and Khurda (n=84) districts of Odisha,
147 India.

148 **2. Methods**

149 *2.1. Household-level sampling and data collection*

150 Villages were randomly selected within a 40 km area of the Odisha state capital,
151 Bhubaneswar. The villages were within a high potential dairying zone which was
152 characterized by sufficient water, market access, and relatively reliable animal health
153 infrastructure. Cattle owning households (n=115) were purposively sampled from Puri (n=31)
154 and Khurda (n=84) districts. Local community leaders helped to identify cattle owning
155 households. A portion (n=35) of the sampled households were found to be affected by FMD
156 in the 12-months preceding the interview. A total of 47 crossbred Jersey cows were identified
157 as being affected. Surveys were conducted in the local language (Oriya) with responses being
158 translated into English at the time of the interview. A voice recorder ensured all interviews
159 were recorded verbatim. Interviews were transcribed into Microsoft Access 2010.

160 2.2. *The interview*

161 Farmers were asked a range of questions detailing their dairy operation. Demographic and
162 socio-economic information of sampled households is provided in York *et al.* (2016). For
163 each cow, farmers were asked to detail milk production (L/cow/day) for each month of the
164 12-month period preceding the interview. A milk density factor of 1.033 (International Farm
165 Comparison Network, 2015) was used to convert milk yields into kg/day. Where possible,
166 farmer responses were corroborated with farm-level records of milk sales provided by local
167 milk collection agents. The records contained sales information only. It was necessary to rely
168 on farmer recall to estimate the quantity of milk kept for household consumption. The milk
169 yield of each sampled cow was not directly measured as it was not possible for the research
170 team to be present in each village at the time of milking (morning and evening) throughout
171 the entire lactation period.

172 Farmers estimated the quantity (kg/cow/day) of each item fed throughout the year. An
173 inventory of the feed offered to cattle was developed for each cow throughout the year. The
174 research team included an individual capable of identifying the various feed items in the event
175 that farmers were unable to identify the feed item and/or provided a local language name.

176 2.3. *FMD outbreak*

177 The surveyed villages experienced an outbreak of FMD with the earliest cases being
178 identified in July (early rainy season). No indigenous (non-descript) cows (n=15) kept by
179 sampled households were infected. Participation in the government subsidized vaccination
180 program prior to the FMD outbreak was variable between households. Following the first
181 confirmed cases a widespread vaccination program was implemented at which time all
182 sampled households had their cloven hooved livestock (cattle, sheep and goats) vaccinated.
183 Table 1 outlines the number of infected cows and prevalence of FMD amongst the sampled
184 households.

185 The feed intake of infected cows would be expected to reduce during periods of FMD
186 infection due to lesions in the mouth and on the tongue. Reduced feed intakes would reduce
187 GHG emission. The extent of intake reductions could not be determined as farmers were
188 unable to estimate the difference in feeding strategies during periods of infection.

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199 **Table 1:** The number of crossbred Jersey cows infected with Foot and Mouth Disease (FMD) within the
200 sampled households of Puri and Khurda districts in Odisha, India. The total number of crossbred Jersey cows
201 sampled and the prevalence of FMD within the sampled population is also provided (mean \pm SD).

District	Village	Households sampled	Cattle sampled	Cattle infected	Prevalence (%)
Puri	Kalapanchana	25	17	1	5.88
	Madhi Brahmapur	6	2	1	50
Khurda	Kendubilwa	23	44	16	36.36
	Nana Kara	17	30	12	40
	Raula	29	31	10	32.26
	Saheb Nagar	2	1	0	0
	Uparashai	13	29	7	24.14
Total number		115	154	47	30.52 \pm 18.24

202

203 *2.4. Calculating level of productivity*

204 The lactation curve of the sampled uninfected cows (n=52) and FMD infected cows (n=36)
205 were used to determine:

- 206
- average milk production throughout the year
 - 207 • quantity of milk lost during an FMD outbreak,
 - 208 • and the length of infection (as indicated by a restoration in milk yield).

209

210 The quantity of milk lost during infection does not include the losses associated with the
211 cows which died ($n = 3$) or were sold ($n = 4$). Thus, the overall loss in productivity could be
212 much greater than currently being examined if these cows were to be included. Similarly,
213 cows which did not recover to pre-infection levels ($n = 5$), stopped lactating completely ($n =$
214 2) died ($n = 3$) or were sold prior to recovery ($n = 4$) were excluded from length of infection
215 calculations.

216 The average milk production of uninfected crossbred Jersey cows was 1237 kg/cow/lactation
217 ($n=52$, $SD = 620.81$). The average lactation length was 250 days. FMD infected crossbred
218 Jersey cows yielded on average 1199 kg/cow/lactation ($n=36$, $SD = 555.27$). Indeed, this
219 appears as only a minor reduction in yield. However, the FMD infected cows were above
220 average yielding animals. Immediately prior to infection average yield was 6.1 kg/cow/day
221 ($SD = 1.99$). The FMD affected cows were assumed to reflect productivity under conditions
222 in which no FMD control had been in place.

223 A portion of the decline in milk yield during FMD infection can be attributed to normal
224 declines expected as the lactation progresses (Moran, 2005). The normal rate of decline was
225 calculated from the lactation curves of the sampled healthy Jersey crossbred cows present for
226 the entire 12-months preceding the interview ($n=52$). The average normal rate of decline in
227 milk yield was found to be 0.8 kg/month (12.7% per month, $SD = 0.50$). The quantity of milk
228 loss attributed to FMD infection was reduced by the monthly normal rate of milk decline for
229 the duration of the infection.

230 The duration of reduced milk yield due to FMD was 1.71 months ($SD = 0.76$). As the
231 majority of infections were noted in the rainy season (June – September) it was assumed milk
232 yield would be reduced for the months of June and July. Therefore, the entire month of June
233 (30 days) and a portion of July (71% or 22 days) would experience reduced milk yields.
234 Based on these assumptions, the total quantity of milk lost during an outbreak of FMD was
235 found to be 183 kg/cow/outbreak. Therefore, control of FMD will increase the productivity of
236 cows from 1199 kg/cow/lactation to 1382 kg/cow/lactation. The parameters and calculations
237 required to determine the level of improvement in milk yield following the control of FMD is
238 provided in Table 2.

239

240 **Table 2:** The parameters and calculations required to determine the level improvement in milk yield following
 241 the control of Foot and Mouth Disease (FMD) in Odisha, India.

Parameter	Calculation method	Value	Standard deviation	Unit
Uninfected cow	Field data (n = 52)	1237	620.81	kg/cow/lactation
Normal rate of decline	Field data (n = 52)	0.8	0.50	kg/cow/day
FMD infected cow	Field data (n = 36)	1199	555.27	kg/cow/lactation
Production lost during infection	Field data (n = 29)	4.89	2.55	kg/cow/day
Duration of reduced yield	Field data (n = 22)	1.71	0.76	Months
Duration of reduced yield	Field data (n = 22)	52	0.76	Days
Normal quantity lost over 1.71 months	Duration of reduced yield (months) x Normal rate of decline	1.37	-	kg/cow/day
Loss due to FMD infection	Production lost during infection – Normal quantity lost over 1.71 months	3.52	-	kg/cow/day
Total quantity lost during a FMD outbreak	Loss due to FMD infection x Duration of reduced yield (days)	183	-	kg/cow/outbreak
Yield following FMD control	Total quantity lost during a FMD outbreak + FMD infected cow	1382	-	kg/cow/lactation

242

243 For comparability, it was assumed that the herd would consist of four adult crossbred Jersey
 244 cows. Using the prevalence of FMD infection across the sampled villages (30.52%) it was
 245 assumed that only one lactating cow would be affected. However, such a scenario does not
 246 reflect the highly contagious nature of FMD. A second scenario was considered assuming that
 247 all four cows were infected. The parameters used to inform each scenario are provided in
 248 Table 3. As high producing cows were found to be more susceptible to FMD infection it was
 249 assumed that the FMD control would increase production to 1382 kg/cow/lactation.

250 The installation of smallscale anaerobic digesters would not have any direct influence on the
 251 productivity of cows. It was assumed that the productivity of the cows would remain the same
 252 as outlined in Table 3.

253 **Table 3:** The effect of Foot and Mouth Disease (FMD) on milk yields as considered in two scenarios
 254 representing different rates of infection in a herd of four cows in Odisha, India.

255

		Level of production (kg/lactation)			
		Scenario 1		Scenario 2	
		No FMD	FMD	No FMD	FMD
		control	controlled	control	controlled
258	Cow 1	1199	1380	1199	1382
259	Cow 2	1237	1237	1199	1382
260	Cow 3	1237	1237	1199	1382
261	Cow 4	1237	1237	1199	1382
261	Total herd production	4910	5091	4796	5528

262 Scenario 1 = one adult cow was assumed to be infected with FMD as determined from prevalence of the disease
 263 in the sampled sites; Scenario 2 = all adult cows were assumed infected with FMD as expected by the highly
 264 contagious nature of FMD.

265 *2.5. Calculating total GHG emissions*

266 A detailed account of emission calculation is provided in York (2017). A summary of the
 267 methods employed is provided.

268 *2.5.1. Enteric methane emissions*

269 Methane emissions were based on the quantity of feed offered to animals relevant to the dairy
 270 sector. Feeding strategies were provided by farmers. The nutritional value of each feed item
 271 was determined from Feedipedia (2012). Average emission estimates were derived on a per
 272 head basis with the use of IPCC (2006a) protocols. However, the Indian specific Methane
 273 Conversion Factor (MCF) (Singhal *et al.*, 2005; Jha *et al.*, 2011) was used.

274 Adult cow emissions were scaled to reflect the different productive states over a 12-month
 275 period. Lactation length was determined from field data (n=78) and found to be an average of
 276 250 days (SD = 78.95) for Jersey crossbred cows. Scaling was achieved by dividing the
 277 annual Methane Emission Factor (MEF) by the number of days per year (i.e. 365) to obtain a
 278 daily MEF for lactating and non-lactating periods. The daily MEFs were then multiplied by
 279 the average length of the lactation (250 days) and dry periods (115 days). The figures were
 280 added to provide an annual MEF. Only emissions of crossbred Jersey cows were considered
 281 as no indigenous (non-descript) cows were affected by FMD. The MEF used to inform the

282 analysis for each category of Jersey crossbred relevant to the dairy sector is provided in Table
283 4.

284 2.5.2. Manure methane emissions

285 Manure methane emissions were calculated based on IPCC (2006a) protocols. However, the
286 Indian specific value for ash (17%) (Gaur *et al.*, 1984) was used. Volatile Solid (VS) content
287 was calculated from feed offered to the animal with the use of IPCC (2006a) protocols. To
288 calculate the Manure Methane Emission Factor (MMEF), it was assumed all manure was
289 either made into dung cakes or placed into an anaerobic digester. The IPCC (2006a) formula
290 was adapted by removing the weighting factor (Equation 1)). The manure emissions from
291 adult cows were scaled (as outlined in Section 2.5.1) to account got lactation and non-
292 lactation periods.

293 **Equation 1:** The adapted IPCC (2006a) equation used to determine the total quantity of methane emitted per
294 cow as determined from feed offered to sampled cows in Odisha, India.

$$295 \quad \text{Manure Methane Emission Factor} = [VS * 365] * \left[B_o * 0.67 \text{kg/m}^3 * \frac{\text{MMCF}}{100} \right]$$

296

297 Manure Methane Emission Factor = annual CH₄ emission, kg CH₄/cow per year

298 VS = daily volatile solid content of Indian dairy cow manure, kg per day

299 365 = basis for calculating annual VS production, days per year

300 B_o= maximum methane producing capacity for manure produced by an Indian dairy
301 cow, 0.13 m³ CH₄ per kg of VS excreted

302 0.67 = conversion factor of m³ CH₄ to kilograms CH₄

303 MMCF = assumed manure methane conversion factor for a specific manure
304 management technique, %

305 Dung cake making was selected as the manure management strategy for comparison as it is
306 the dominant manure management system in the sampled sites (Government of India, 2011a).

307 The Manure Methane Conversion Factor (MMCF) for dung cake making was assumed to be
308 10% (IPCC, 2006a). The MMCF is used to indicate the extent to which maximum methane
309 producing capacity (B_o) is achieved under a specific manure management system (IPCC,
310 2006a). As outlined in Eq. (1), B_o is assumed to be 0.13 m³ CH₄ per kg of VS excreted.

311 The MMCF for the anaerobic digester was determined from the rate of leakage

312 (Khoiyangbam *et al.*, 2004; Khoiyangbam, 2008; Bruun *et al.*, 2014) based on the works of

313 Khoiyangbam (2008) and Khoiyangbam *et al.* (2004). Ideally, leakage would have been
314 measured directly. However, the logistics and resources associated with measuring leakage
315 from a large number of anaerobic digesters was beyond the scope of this investigation. As
316 such, it was assumed that the leakage measured by Khoiyangbam (2008) and Khoiyangbam *et*
317 *al.* (2004) (and also used by Bruun *et al.* (2014) provided a sufficiently robust estimate.

318 The MMCF offered by Bruun *et al.* (2014) (i.e. 17%) could not be used as the author assumed
319 that 0.4 m³ of biogas is produced per m³ of digester size. Based on this assumption, to
320 calculate methane leakage as a percentage of total production in a 2 m³ system, 0.8 m³ of
321 biogas is produced per day. As biogas is 60% methane (Khoiyangbam *et al.*, 2004;
322 Khoiyangbam, 2008; Bruun *et al.*, 2014) a total of 0.48 m³ of methane is produced per day.
323 Following a conversion to kilograms via a conversion factor of 0.67 (IPCC, 2006a) and
324 extrapolation across an entire year (365 days), annual methane production would be 117.38
325 kg CH₄/year. As such, the measured leakage of 53.2 kg CH₄/year would represent 45.32% of
326 total methane produced.

327 A simplified approach was developed to represent the measured leakage as a percentage of
328 total methane production (i.e. MMCF). It was assumed that that the system under
329 investigation (2 m³) was achieving maximum methane production. The maximum methane
330 producing ability of cow manure (0.13 m³ CH₄/kg VS) (IPCC, 2006a) and VS excretion rate
331 of Indian cows (2.6 kg VS/head/day) (IPCC, 2006a) were used. It was assumed four cows
332 were required to produce sufficient manure to ensure maximum working capacity. A total of
333 1.35 m³ CH₄/day was calculated to be produced. Yearly methane production was calculated to
334 be 493.48 m³. This value was converted to kilograms of a methane via a conversion factor of
335 0.67 (IPCC, 2006a). Total production was found to be 330.63 kg CH₄/year. Therefore,
336 leakage of 53.2 kg CH₄/year represents 16.09% of the total amount possible.

337 This method of converting digester leakage estimates to a MMCF was then applied to the
338 leakage estimate offered by Khoiyangbam *et al.*, (2004). Khoiyangbam *et al.*, (2004) found
339 methane leakage from a 2 m³ Deenbandhu system to be 46.4 kg CH₄/year. Only leakage from
340 the fixed dome Deenbandhu system was considered as this is the most common type of
341 digester installed in India (Government of India, 2002). The calculation was repeated to
342 convert the value provided by Khoiyangbam (2008) to a MMCF. An average of the newly
343 calculated MMCFs (i.e. 14.0% (Khoiyangbam *et al.*, 2004) and 15.2% (Khoiyangbam, 2008))
344 was calculated. The average MMCF used in this analysis for anaerobic digestion was 14.6%.

345 N₂O emissions from manure were not included in this investigation as the manure
346 management systems under investigation (i.e. anaerobic digestion, dung cake making) are not
347 expected to emit N₂O (IPCC, 2006a). Additional methane emission is also expected for any
348 manure that is left stacked in piles prior to dung cake making. These sources were not
349 included as they are expected to be relatively minor (Government of India, 2012a), Table 4
350 provides the MMEF for each category of Jersey crossbred cattle relevant to the dairy sector if
351 the manure is managed as dung cakes or anaerobic digestion.

352 *2.6. Calculating methane emission intensity*

353 Emission intensity is a measure of GHG emission in terms of productive output. As the
354 slaughter of cattle is illegal in Odisha (Government of Odisha, 1961) it was assumed that the
355 total quantity of GHG emitted can be assigned to milk production.

356 To ensure comparability between anaerobic digestion and FMD control, it was necessary to
357 assume that households kept four adult cows. This is the number of adult cows required to
358 produce sufficient manure for maximum anaerobic digester functionality (assuming a system
359 size of 2 m³). However, the calculation of emission intensity requires inclusion of emissions
360 from non-productive components of the herd. The total number of cattle sampled was used to
361 indicate the number of non-productive cattle kept per adult cow. For example, for every adult
362 cow sampled, 0.27 young heifers were sampled.

363 Due to the inclusion of non-productive cattle in the herd, more manure will be produced than
364 can be utilised by a 2 m³ Deenbandhu anaerobic digester. It was assumed excess manure
365 (from non-productive cattle) will be managed as dung cakes. All manure produced from the
366 four adult cows was assumed to be available for use in the anaerobic digester or made into
367 dung cakes. The interval of use (i.e. time taken to make into dung cakes, or load into the
368 digester) was not considered as emissions were not expected from these sources (Government
369 of India, 2012a). The herd size and structure is shown in Table 4.

370 Emission factors were scaled to herd structure (Table 4). Scaling was necessary as emission
371 factors are reported on a per head basis. Scaling was achieved by multiplying the number of
372 animals kept per four adult cows via the MEF, MMEF under dung cake making, and MMEF
373 under anaerobic digestion. For example, the MEF of male calves (6.33 kg CH₄/year) was
374 multiplied by the number of male calves (i.e. 0.41) kept.

375 Total methane production was converted to CO₂ equivalents by multiplication of the emission
 376 estimate and the GWP of methane at a 100 year timeframe (IPCC, 2013). The GWP of CH₄
 377 was assumed to be 25 (IPCC, 2007). The methane emission intensity was calculated by
 378 dividing the CO₂ equivalents by the total quantity of milk produced from the herd under the
 379 different manure management and disease scenarios.

380 **Table 4:** The average Methane Emission Factors (MEF) and Manure Methane Emission Factors (MMEF)
 381 calculated from the diets of cattle subject to smallholder conditions in Odisha, India. Manure Methane Emission
 382 Factors (MMEF) are provided for dung cake making and anaerobic digestion, Methane Emission Factors (MEF)
 383 and Manure Methane Emission Factors (MMEF) are provided in kg of methane/animal per year. The herd
 384 structure assumed for the comparison of GHG emission mitigation policies is also provided

	Sample size (n)	MEF	MMEF _{Cake}	MMEF _{Digester}	Herd structure calculation	Herd structure
Cow ^a	116	43.91	7.74	10.88	-	4
Male calf	12	6.33	0.85	-	(Male calf÷Cow)x4	0.41
Female calf	14	15.89	2.24	-	(Female calf÷)*4	0.48
Young heifers	31	21.74	2.99	-	(Young heifer÷Cow)x4	1.07
Older heifers	22	25.02	3.45	-	(Older heifer÷Cow)x4	0.76
Young males	1	6.35	0.82	-	(Young male÷Cow)x4	0.03
Total herd size	-	-	-	-		6.76

385
 386 Male calf = < 1 year old; Female calf = < 1 year old; Young heifer = 1 year - < 2.5 years; Older heifers = >2.5
 387 years (not calved); Young males = 1 year - < 2.5 years.

388 MEF = Estimate based on the Methane Conversion Factor (MCF) provided by (Singhal *et al.*, 2005; Jha *et al.*,
 389 2011)

390 MMEF_{Cake} = Estimate based on the Indian specific value for ash (17%) (Gaur *et al.*, 1984) assuming MCF for
 391 dung cake making is 10% (IPCC, 2006a).

392 MMEF_{Digester} = Estimate based on the Indian specific value for ash (17%) (Gaur *et al.*, 1984) assuming MCF for
 393 anaerobic digestion is 14.6%.

394 *Indicates that the manure will be made into dung cakes and assigned the MMEF_{Cake}.

395 ^aThe estimates of methane emission have been scaled to account for a lactation period of 250 days and dry
 396 period of 115 days.

397 **3. Results**

398 *3.1.Herd emission*

399 Table 5 provides the contribution to emissions made by each category of Jersey crossbred
 400 within the herd. Table 5 indicates that enteric emissions are the most important source of
 401 emissions. Manure methane emission of adult cows represents 17.6% and 24.8% of enteric
 402 emissions when manure is managed as dung cakes and anaerobic digestion, respectively.

403 **Table 5:** The enteric methane and manure methane emissions calculated from the diets of cattle subject to
 404 smallholder conditions in Odisha, India. Manure is managed as dung cakes or anerobic digestion.

	Scaled contribution to emission intensity (kg CH ₄ /year)			405
	Enteric emission ^a	Manure emission – Dung cakes ^b	Manure emission – Digester ^c	406
				407
Cow	175.64	30.96	43.52	408
Male calf	2.62	0.35	0.35	409
Female calf	7.67	1.08	1.08	410
Young heifers	23.24	3.20	3.2	411
Older heifers	18.98	2.62	2.62	412
Young males	0.22	0.03	0.03	413
Total	228.37	38.23	53.75	414
CO ₂ eq (kg CO ₂ eq/year)	5709.23	955.87	1343.85	415
				416
				417
				418
				419
				420

421 Male calf = < 1 year old; Female calf = < 1 year old; Young heifer = 1 year - < 2.5 years; Older heifers = >2.5
 422 years (not calved); Young males = 1 year - < 2.5 years.

423 ^a Estimate based on the Methane Conversion Factor (MCF) provided by Jha *et al.*, (2011) and Singhal *et al.*,
 424 (2005)

425 ^b Estimate based on the Indian specific value for ash (17%) (Gaur *et al.*, 1984) assuming MCF for dung cake
 426 making is 10% (IPCC, 2006a).

427 ^c Estimate based on the Indian specific value for ash (17%) (Gaur *et al.*, 1984) assuming MCF for anaerobic
 428 digestion is 14.64%.

429 *3.2.Emission intensity and mitigation*

430 Table 26 provides the methane emission intensity of milk production in Odisha India. Control
 431 of FMD reduces the methane emission intensity. However, the extent of reduction is
 432 dependent on the scenario considered. Scenario 1 (only one adult cow infected) results in a

433 minor reduction in emission intensity (3.68%) whilst Scenario 2 (all adults infected) results in
 434 a more significant reduction of 12.95%. The installation of a smallscale anaerobic digester
 435 will increase GHG emission intensity by between 4.41-5.01%.

436

437 **Table 2:** The emission intensity of milk production in Odisha, India under different emission mitigation
 438 strategies. Mitigation strategies include Foot and Mouth Disease (FMD) control and installation of smallscale
 439 anaerobic digesters.

Scenario 1		Value	Unit
No FMD control	Manure managed as dung cakes	1.36	kg CO ₂ eq/kg milk
	Manure managed in anaerobic digester	1.44	kg CO ₂ eq/kg milk
FMD controlled	Manure managed as dung cakes	1.31	kg CO ₂ eq/kg milk
	Manure managed in anaerobic digester	1.39	kg CO ₂ eq/kg milk
Change in emission intensity following anaerobic digester installation		+5.50	%
Change in emission intensity following FMD control		-3.56	%
Scenario 2			
No FMD control	Manure managed as dung cakes	1.39	kg CO ₂ eq/kg milk
	Manure managed in anaerobic digester	1.47	kg CO ₂ eq/kg milk
FMD controlled	Manure managed as dung cakes	1.21	kg CO ₂ eq/kg milk
	Manure managed in anaerobic digester	1.28	kg CO ₂ eq/kg milk
Change in emission intensity following anaerobic digester installation		+5.50	%
Change in emission intensity following FMD control		-13.12	%

440 Scenario 1 = one adult cow was assumed to be infected with FMD as determined from prevalence of the disease
 441 in the sampled sites; Scenario 2 = all adult cows were assumed infected with FMD as expected by the highly
 442 contagious nature of FMD.

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448 **Table 6:** The emission intensity of milk production in Odisha, India under different emission mitigation
 449 strategies. Mitigation strategies include Foot and Mouth Disease (FMD) control and installation of smallscale
 450 anaerobic digesters.

Scenario 1		Value	Unit
No FMD control	Manure managed as dung cakes	1.36	kg CO ₂ eq/kg milk
	Manure managed in anaerobic digester	1.42	kg CO ₂ eq/kg milk
FMD controlled	Manure managed as dung cakes	1.31	kg CO ₂ eq/kg milk
	Manure managed in anaerobic digester	1.37	kg CO ₂ eq/kg milk
Change in emission intensity following anaerobic digester installation		+4.41	%
Change in emission intensity following FMD control		-3.68	%
Scenario 2		Value	Unit
No FMD control	Manure managed as dung cakes	1.39	kg CO ₂ eq/kg milk
	Manure managed in anaerobic digester	1.46	kg CO ₂ eq/kg milk
FMD controlled	Manure managed as dung cakes	1.21	kg CO ₂ eq/kg milk
	Manure managed in anaerobic digester	1.26	kg CO ₂ eq/kg milk
Change in emission intensity following anaerobic digester installation		+5.01	%
Change in emission intensity following FMD control		-12.95	%

451 Scenario 1 = one adult cow was assumed to be infected with FMD as determined from the prevalence of the
 452 disease in the sampled sites; Scenario 2 = all adult cows were assumed infected with FMD as expected by the
 453 highly contagious nature of FMD.

454 **4. Discussion**

455 *4.1 Emission intensity*

456 The development of robust measures of emission intensity is a necessary first step from which
 457 mitigation can be considered. The calculated emission intensities (i.e. 1.26-1.46 kg CO₂
 458 eq/kg milk) are higher than existing methane estimates for Indian crossbred dairy cows (0.53-
 459 0.70 kg CO₂ eq/kg of milk (Swamy and Bhattacharya, 2006; Jha et al., 2011). However, the
 460 comparability is limited due to the incompleteness of previous research (as discussed in
 461 Section 1). Additionally, the cows included in this investigation were Jersey crossbred cows.
 462 It is unlikely that this cow type is comparable to ‘crossbred’ cows (most likely Holstein
 463 Friesian crossbreds) considered by previous authors (see Swamy and Bhattacharya, 2006; Jha
 464 et al., 2011).

465 *4.2 Mitigation*

466 The results clearly demonstrate the efficacy of different policy based interventions in
 467 altering the methane emission intensity of milk production. The control of FMD was found to

468 reduce emission intensity by 3.68-12.95% whilst the installation of a smallscale anaerobic
469 digester was found to increase emission intensity by 4.41-5.01%. The ineffectiveness of the
470 anaerobic digester is due to the comparatively climate change-benign nature of traditional
471 Indian manure management practices (i.e. making dung cakes). If manure was managed in its
472 liquid form, as is the case in intensive production systems of the global north, the installation
473 of anaerobic digesters would be a more effective mitigation strategy than identified by this
474 investigation. Thus, smallscale anaerobic digesters lack contextual relevance and are ill-
475 suited to achieving emission reductions within the Indian smallholder dairy sector.

476 Conversely, the control of FMD resulted in a reduction in emission intensity. Indeed, it is
477 unsurprising that attempts to improve productivity (via improved health) reduces emission
478 intensity. Yet, Indian livestock policy is silent on the mitigation co-benefit that can result
479 from improved animal health. The results highlight the need for policymakers to explicitly
480 recognise the importance of the mitigation co-benefit associated with FMD control and
481 animal health policies more generally.

482 A number of authors discuss the potential usefulness of improved health as a means of
483 reducing emission intensity (see Gerber et al., 2013; Hristov et al., 2013). However, northern
484 production systems have primarily been the focus of studies. For example, using a LCA in
485 Spain, Hospido and Sonesson (2005) found control of mastitis to have a positive effect on
486 GHG emissions. Similarly, in the United Kingdom Stott *et al.* (2010) found a mastitis control
487 program could achieve a 1.5-2% improvement in productivity which reduced UK dairy sector
488 emissions by 8% (0.4 Mt CO₂ eq). Such results are largely unsurprising as the core outcome
489 of improved animal health is improved productive efficiency. Studies highlight the
490 importance of enhanced productivity in achieving dairy sector emission intensity reductions
491 (eg Beukes *et al.*, 2010; Bell *et al.*, 2013). Thus, it is the current low levels of productivity
492 which make the smallholder sector particularly responsive to such interventions.

493 Biogas leakage from anaerobic digesters has been an area of increasing research interest (e.g.
494 Khoiyangbam *et al.*, 2004; Khoiyangbam, 2008; Bruun *et al.*, 2014). However, previous
495 studies have been unable to estimate the importance of this leakage to increasing dairy sector
496 GHG emissions. Rather, studies have focused on the effect of anaerobic digester installation
497 on total emissions (Bhattacharya *et al.*, 1997; Pathak *et al.*, 2009). In doing so, the authors
498 have ignored important gaps in knowledge with regard to baseline estimates of digester
499 leakage. By not recognising the importance of digester leakage (compared to existing manure

500 management strategies) such studies have overestimated the likely reduction in GHG
501 emission that can be achieved by digester installation.

502 Additionally, as biogas leakage occurs prior to combustion this source of emission must be
503 assigned to the dairy sector (IPCC, 2006b). AS a result, net emissions from the energy sector
504 are reduced (via a substitution of burning fossil fuels and/or firewood) to the detriment of
505 dairy sector emissions. This is concerning as there are currently no interventions available
506 that can directly (and easily) reduce dairy sector emissions. Yet, there are alternate mitigation
507 options available to the energy sector (eg solar). Thus, it may be advantageous to utilise
508 methods within the energy sector that do not transfer emissions into the dairy sector due to the
509 difficulties in mitigating dairy sector emissions.

510 Alternatively, it may be necessary to redesign the anaerobic digesters to reduce the risk of
511 leakage. This is advantageous as emissions could be reduced to zero as noted in northern
512 large scale anaerobic digesters (eg Kaparaju and Rintala, 2011). Redesigning the anaerobic
513 digester will also ensure that the significant benefits accrued to the household following
514 installation are retained.

515 There are significant gaps in knowledge regarding methane emissions from dung cakes and
516 the extent to which leakage is a problem for anaerobic digesters. Thus, there is an inherent
517 level of uncertainty arising from such gaps in knowledge. Specifically, this investigation
518 assumes that the maximum methane emission is achieved during anaerobic digestion.
519 Although the assumption is logical as the objective of anaerobic digestion is to provide
520 conditions conducive to methane production, it is possible that maximum methane emission is
521 not achieved. For example, manure managed in a lagoon system has a MCF of 78% (at 21⁰C)
522 (IPCC, 2006a). Therefore, the current study may underestimate the importance of the leakage
523 measured by Khoiyangbam *et al.*, (2004) and Khoiyangbam (2008). As such, future research
524 should explicitly consider leakage as a percentage of total methane produced during digestion.
525 Additionally, although the measures provided by Khoiyangbam *et al.*, (2004) and
526 Khoiyangbam (2008) are average annual estimates, methane emission is temperature
527 dependent. Variability in the rate of leakage should also be considered.

528 Therefore, further research is urgently required in two key areas. Firstly, emissions arising
529 during dung cake making must be accurately measured to ensure that this method of manure
530 management is as climate-change-benign as authors assume it to be (USEPA, 1992; IPCC,
531 2006a; Government of India, 2010). Secondly, a thorough evaluation of biogas production

532 potential and leakage (including direct measurement) must be undertaken to gain a better
533 understanding of the usefulness of smallscale anaerobic digesters in terms of GHG emission
534 reduction from the dairy sector. The outcomes of such research will inform future revision of
535 IPCC values.

536 The study is also limited by relatively simple calculations used to predict milk yield following
537 the control of FMD. Such calculations are likely subject to large uncertainty as suggested by
538 the milk yield standard deviations. As such, future research should include a sensitivity
539 analysis and statistical analysis to better understand the significance of FMD impacts on milk
540 yields. Nonetheless, this study is an important contribution to knowledge as it an important
541 proof of concept that demonstrates the importance of developing contextually relevant
542 mitigation strategies. By not adequately considering baseline emission scenarios,
543 policymakers risk the use of ill-suited interventions which will inevitably fail to deliver
544 desired outcomes.

545 Importantly, the study indicates that a reduction in overall population size is not required to
546 achieve a reduction in emission intensity. It is recommended policymakers further explore
547 productivity improving interventions (eg FMD control) to identify and exploit co-benefit
548 mitigation opportunities. However, within the socio-cultural context of India questions
549 remain as to whether emission intensity reductions will ever be large enough to precipitate a
550 decline in total emissions due to the unpalatability of a reduced national dairy herd and
551 increasing demand for milk products (Delgado et al., 1999; Pica-Ciamarra and Otte, 2009).

552 In conclusion, this study highlights the need for policymakers to take a multi-disciplinary
553 approach to emission mitigation by implementing a broad agenda considering a range of
554 sectors and their interactions. By installing smallscale anaerobic digesters, emissions are
555 moved from the energy sector into the dairy sector where they are inherently difficult to
556 mitigate. Improving animal health will reduce the emission intensity of milk production with
557 no immediate overall effect on net emissions. Where the impacts of an intervention appear
558 discrete and there is no movement of emissions to other sectors (such as with FMD control) it
559 should be pursued. However, where an interaction between sectors is noted, care must be
560 taken as to move emissions into a sector where they are difficult to mitigate (e.g. the dairy
561 sector) may limit the long-term usefulness of the strategy. Indeed, the movement of emissions
562 between sectors is a purely political exercise. Yet, a failure to recognise such political
563 manoeuvring will likely limit the cost-effectiveness of economy wide emission reduction.

564 **Acknowledgements**

565 The authors would like to thank Dr. Soumya Pani and Dr. Niranjana Panda from the Orissa
566 University of Agriculture and Technology and the secretary of the Women's Federation,
567 Sabita Sethy, for their advice and support during field activities. The authors also thank the
568 participant farmers for their patience and willingness to aid the research. Funding was
569 provided by the Harriett Beard Travelling Scholarship from the University of Sydney which
570 had no influence on any aspect of the study. The research was conducted as approved by the
571 Ethical Clearance Board of the University of Reading, UK (reference number: APD – B141)

572 **5. References**

- 573 Adler, A.A., Doole, G.J., Romera, A.J., Beukes, P.C., 2013. Cost-effective mitigation of
574 greenhouse gas emissions from different dairy systems in the Waikato region of New
575 Zealand. *J. Environ. Manage.* 131, 33-43.
- 576 Bell, M.J., Eckard, R.J., Haile-Mariam, M., Pryce, J.E., 2013. The effect of changing cow
577 production and fitness traits on net income and greenhouse gas emissions from Australian
578 dairy systems. *J. Dairy Sci.* 96, 7918-7931.
- 579 Beukes, P.C., Gregorini, P., Romera, A.J., Levy, G., Waghorn, G.C., 2010. Improving
580 production efficiency as a strategy to mitigate greenhouse gas emissions on pastoral dairy
581 farms in New Zealand. *Agr. Ecosyst. Environ.* 136, 358-365.
- 582 Bhattacharya, S.C., Thomas, J.M., Abdul Salam, P., 1997. Greenhouse gas emissions and the
583 mitigation potential of using animal wastes in Asia. *Energy* 22, 1079-1085.
- 584 Bruun, S., Jensen, L.S., Khanh Vu, V.T., Sommer, S., 2014. Small-scale household biogas
585 digesters: An option for global warming mitigation or a potential climate bomb? *Renew. Sust.*
586 *Energ. Rev.* 33, 736-741.
- 587 Capper, J.L., Cady, R.A., Bauman, D.E., 2009. The environmental impact of dairy
588 production: 1944 compared with 2007. *J. Anim. Sci.* 87, 2160-2167.
- 589 Datta, T.N., Shrestha, Chokkalingam, G., 2015. Agricultural land and bovine population in
590 India: A critical review of agricultural census data. *J. Rural Develop.* 34, 167 - 186.
- 591 Delgado, C.L., Rosegrant, M.W., Steinfeld, H., Ehui, S.K., Courbois, C., 1999. Livestock to
592 2020: the next food revolution. International Food Policy Research Institute (IFPRI) 61.
- 593 Doole, G.J., 2014. Least-cost greenhouse gas mitigation on New Zealand dairy farms. *Nutr.*
594 *Cycl. Agroecosys.* 98, 235-251.

595 FAO, 2010. Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment.
596 Food and Agricultural Organization of the United Nations, Rome, Italy.

597 FAO, 2013. FAOSTAT Emissions Database. Food and Agricultural Organization of the
598 United Nations.

599 Feedipedia, 2012. Feedipedia - Animal feed resources information system. French National
600 Institute for Agricultural Research (INRA), Centre de coopération internationale en recherche
601 agronomique pour le développement (CIRAD), Association Française de Zootechnie(AFZ)
602 and Food and Agricultural Organization of the United Nations (FAO).

603 Foster, C., Audsley, E., Williams, A., Webster, S., Dewick, P., Green, K., 2007. The
604 environmental, social and economic impacts associated with liquid milk consumption in the
605 UK and its production: a review of literature and evidence. Department for Environment,
606 Food and Rural Affairs, London, UK.

607 Gaur, A.C., Neelakantan, S., Dargan, K.S., 1984. Organic manures. Indian Council of
608 Agricultural Research.

609 Gerber, P., Vellinga, T., Opio, C., Steinfeld, H., 2011. Productivity gains and greenhouse gas
610 emissions intensity in dairy systems. *Livestock Science* 139, 100-108.

611 Tackling climate change through livestock - A global assessment of emissions and mitigation
612 opportunities. In: Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J.,
613 Falcucci, A., Tempio, G. (Eds.), 2013. Food and Agriculture Organization of the United
614 Nations, Rome, Italy.

615 Government of India, 2002. Evaluation Study On National Project on Biogas Development.
616 Government of India, New Delhi.

617 Government of India, 2004. India's Initial National Communication to the United Nations
618 Framework Convention on Climate Change. Government of India, New Delhi.

619 Government of India, 2010. India: Greenhouse Gas Emissions 2007. Government of India,
620 New Delhi.

621 Government of India, 2011a. Census 2011 - Percentage of Households to Total Households
622 by Amenities and Assets. Government of India, New Delhi.

623 Government of India, 2011b. Climate change & 12th five year plan: report of sub-group on
624 climate change. Government of India, New Delhi.

625 Government of India, 2011c. Strategic Plan for New and Renewable Energy Sector for the
626 period 2011–2017. Ministry of New and Renewable Energy, New Delhi.

627 Government of India, 2012a. India: Second National Communication to the United Nations
628 Framework Convention on Climate Change. Government of India, New Delhi.

629 Government of India, 2012b. Report of the working group on animal husbandry and dairying
630 12th five year plan (2012 - 17). Government of India, New Delhi.

631 Government of India, 2013. National Livestock Policy 2013. Government of India, New
632 Delhi.

633 Government of India, 2014a. 19th Livestock Census - 2012 - All India report. Government of
634 India, New Delhi.

635 Government of India, 2014b. Basic Animal Husbandry and Fisheries Statistics. Government
636 of India, New Delhi.

637 Government of Odisha, 1961. The Orissa Prevention of Cow Slaughter Act, 1960.
638 Government of Odisha,, Bhubaneswar.

639 Herrero, M., Wirsenius, S., Henderson, B., Rigolot, C., Thornton, P., Havlík, P., de Boer, I.,
640 Gerber, P.J., 2015. Livestock and the Environment: What Have We Learned in the Past
641 Decade? *Annual Review of Environment and Resources* 40, 177-202.

642 Hospido, A., Sonesson, U., 2005. The environmental impact of mastitis: a case study of dairy
643 herds. *Sci. Total Environ.* 343, 71-82.

644 Mitigation of greenhouse gas emissions in livestock production - A review of technical
645 options for non-CO2 emissions. In: Hristov, A.N., Oh, J., Lee, C., Meinen, R., Montes, F.,
646 Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A., Yang, W., Tricarico, J., Kebreab, E.,
647 Waghorn, G., Dijkstra, J., Oosting, S. (Eds.), 2013. Food and Agricultural Organization of the
648 United Nations, Rome, Italy.

649 IPCC, 2006a. Emissions from livestock and manure management. In: Eggleston, H.S.,
650 Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), 2006 IPCC Guidelines for National
651 Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories
652 Programme, Intergovernmental Panel on Climate Change, Kamiyamaguchi, Japan, pp. 10.11-
653 10.89.

654 IPCC, 2006b. N2O Emissions from managed soils and CO2 emissions from Lime and Urea
655 application. In: De Klein, C., Novoa, R.S.A., Ogle, S., Smith, K.A., Rochette, P., Wirth, T.C.,
656 McConkey, B.G., Mosier, A., Rypdal, K. (Eds.), 2006 IPCC Guidelines for National
657 Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories
658 Programme, International Panel on Climate Change, Kamiyamaguchi, Japan, pp. 11.11-11.54.

659 IPCC, 2007. Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing. In:
660 Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller,
661 H.L. (Eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working*

662 Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.
663 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
664 IPCC, 2013. Annex III: Glossary. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M.,
665 Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate
666 Change 2013: The Physical Science Basis Working Group I Contribution to the Fifth
667 Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University
668 Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1447-1465.
669 International Farm Comparison Network, 2015. Calculator. International Farm Comparison
670 Network, Kiel, Germany.
671 Jha, A.K., Singh, K., Sharma, C., Singh, S.K., Gupta, P.K., 2011. Assessment of methane and
672 nitrous oxide emissions from livestock in India. *Journal of Earth Science & Climatic Change*
673 2, 1-12.
674 Kaparaju, P., Rintala, J., 2011. Mitigation of greenhouse gas emissions by adopting anaerobic
675 digestion technology on dairy, sow and pig farms in Finland. *Renew. Energy* 36, 31-41.
676 Khoiyangbam, R.S., Kumar, S., Jain, M.C., Gupta, N., Kumar, A., Kumar, V., 2004. Methane
677 emission from fixed dome biogas plants in hilly and plain regions of northern India.
678 *Bioresource Technol.* 95, 35-39.
679 Khoiyangbam, R.S., 2008. Greenhouse gases emission from energy production in
680 conventional biogas plants in India. *Energy Sources, Part A* 30, 689-697.
681 Knight-Jones, T.J.D., Rushton, J., 2013. The economic impacts of foot and mouth disease –
682 What are they, how big are they and where do they occur? *Prev. Vet. Med.* 112, 161-173.
683 Kristensen, T., Mogensen, L., Knudsen, M.T., Hermansen, J.E., 2011. Effect of production
684 system and farming strategy on greenhouse gas emissions from commercial dairy farms in a
685 life cycle approach. *Livestock Science* 140, 136-148.
686 Moran, J., 2005. Diet and milk production. In: Moran, J. (Ed.), *Tropical dairy farming:*
687 *feeding management for small holder dairy farmers in the humid tropics.* Landlinks Press,
688 Kyabram, Australia, pp. 159-170.
689 Opio, C., Gerber, P., Mottet, A., Falcucci, A., Tempio, G., MacLeod, M., Vellinga, T.,
690 Henderson, B., Steinfeld, H., 2013. Greenhouse gas emissions from ruminant supply chains:
691 A global life cycle assessment. Food and Agriculture Organization of the United Nations,
692 Rome, Italy.
693 Pathak, H., Jain, N., Bhatia, A., Mohanty, S., Gupta, N., 2009. Global warming mitigation
694 potential of biogas plants in India. *Environmental Monitoring and Assessment* 157, 407-418.

695 Patra, A.K., 2012. Estimation of methane and nitrous oxide emissions from Indian livestock.
696 J. Environ. Monitor. 14, 2673–2268.

697 Pica-Ciamarra, U., Otte, J., 2009. The ‘Livestock Revolution’: Rhetoric and reality. Pro-Poor
698 Livestock Policy Initiative, 1-23.

699 Singhal, K.K., Mohini, M., Jha, A.K., Gupta, P.K., 2005. Methane emission estimates from
700 enteric fermentation in Indian livestock: Dry matter intake approach. Curr. Sci. India 88, 119-
701 127.

702 Stott, A., MacLeod, M., Moran, D., 2010. Reducing greenhouse gas emissions through better
703 animal health. Policy Briefing: Rural Policy Centre Scottish Agricultural College, 1-8.

704 Swamy, M., Bhattacharya, S., 2006. Budgeting anthropogenic greenhouse gas emission from
705 Indian livestock using country-specific emission coefficients. Curr. Sci. India 91, 1340-1353.

706 Global methane emission from livestock and poultry manure. In: USEPA (Ed), US
707 Environmental Protection Agency, Washington DC.

708 Webb, J., Audsley, E., Williams, A., Pearn, K., Chatterton, J., 2014. Can UK livestock
709 production be configured to maintain production while meeting targets to reduce emissions of
710 greenhouse gases and ammonia? Journal of Cleaner Production 83, 204-211.

711 York, L., Heffernan, C., Rymer, C., 2016. The role of subsidy in ensuring the sustainability of
712 small-scale anaerobic digesters in Odisha, India. Renew. Energ. 96, 1111-1118.

713 York, L., 2017. The Impact of Climate Change on Poor Dairy Producers in Odisha, India.
714 School of Agriculture, Policy and Development, University of Reading, Reading, UK p. 451.

715