Does efficiency improvement offset emissions? Evidence of rebound effect in the global beef production [*]

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Abstract

We use a rebound effect framework to investigate the opposing effects of production efficiency and market forces on global beef demand and consequent changes in emissions. Our results confirm that productivity improvements and market factors partially offset the effects of each other. That is, beef demands and emissions could have been even greater has there not been any productivity improvement over time. Reducing such rebound effects will require policies aiming at greater productivity improvements while taking the opposing effects of market forces into account.

Keywords: Efficiency; Emissions; Livestock; Rebound effect.

JEL Codes: Q18; Q52; Q56; O13; O33.

Highlights

- We identify the presence and extent of rebound effects in the global beef production.
- Production efficiency partially offsets the effects of market forces on the required cattle for beef production.
- It also offsets emissions associated to beef production.

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1. Introduction

Limiting the global temperature increase to 1.5°C as has been set by the Paris Agreement requires concerted efforts from all economic sectors including the agriculture. While the rate of growth in greenhouse gas (GHG) emissions has declined during the last decade, emissions must be reduced by around 7.6 percent per year over the next decades (UNEP 2019). Enteric fermentation from cattle raised for beef production is one of the major sources of methane which is about 84 times more powerful at warming the climate than carbon dioxide in the short term. During the COP26 more than 100 countries agreed to cut their methane emissions by 30% by 2030 under the Global Methane Pledge. However, in the face of population growth and increasing demand, economic sectors are experiencing increasing challenges to keep up with climate goals.

In fact, greater effectiveness of sector-specific policies requires understanding how the market reacts to them. Demand-side forces such as population, income, and market prices are responsible for increasing emissions, and they may undermine the effects of the policies aimed at promoting sustainable growth and improving the environmental performance of the livestock sector that have largely focused on productivity improvements (FAO 2019a; Gerber *et al.* 2013; Steinfeld *et al.* 2006). Moreover, Gerber *et al.* (2013) associated the level and intensity of livestock emissions with the inefficient use of resources, a view shared by Steinfeld *et al.* (2006) who highlighted that improving efficiency is fundamental to reducing the sector's environmental impact. In this context, the Food and Agriculture Organization of the United Nations (FAO) has recently introduced a set of practical actions to reduce the environmental impact of livestock production systems by enhancing the efficient use of resources through improved feeding, genetics, animal health, general husbandry, and information technology (FAO 2019b). Against this backdrop, it is important to identify the net effects of these two opposing factors, productivity improvements and market forces, on livestock demands and consequent emissions. We investigate this issue using a rebound effect framework for the global beef production system.[1]

Our case study focuses on the beef subindustry, which accounts for approximately 40 percent of total livestock emissions (FAO 2019a). We use livestock productivity, defined as beef

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[1] For specific country case studies, it is important to consider both the stock of cattle and slaughtered cattle to reflect on investment demand and consumption demand of livestock. However, our focus is to provide a global analysis and therefore we adopt a simpler framework in this paper.

production per head of cattle, as the measure of resource use efficiency. The concept of rebound effect suggests that the reduction in emissions attributable to efficiency improvements may be overestimated if one fails to consider the behavioral responses of producers and consumers to technical changes (Binswanger 2001). Moreover, efficiency improvements may reduce the relative price of resources, resulting in an increased demand for the associated commodity. This indirect effect will partially offset the reduction in emissions achieved by efficiency gains, resulting in a rebound effect (Greening, Greene, and Difiglio 2000). Furthermore, other market forces, such as increases in population and standard of living, can also trigger rebound effect.

Following the conventional rebound effect literature, we adopt a two-step approach. The first step, often referred to in literature as the engineering calculation, accounts for the direct effects of efficiency improvements and predicts the potential emissions reduction in the livestock sector. The second step, often referred to as the economic calculation, incorporates the efficiency-induced reactions of actors in the market and, therefore, predicts the likely livestock emissions reduction. Our results confirm the presence of an emissions rebound effect in response to efficiency improvements in the global livestock sector. These results are especially important for countries with a high dependence on livestock products; productivity-enhancing strategies, if not properly instrumented, may not achieve the anticipated emissions reductions and may even result in undesirable environmental outcomes.

2. The Global Beef Production

The livestock sector is the world’s fastest-growing agricultural subsector (FAO 2018). According to the Organisation for Economic Co-operation and Development (OECD), livestock production is projected to expand by around 15 percent during the next decade, driven by economic and population growth (FAO 2019a). By 2028, global beef production is expected to increase by about 9 Mt, facilitated by both increased demand and improved productivity. However, the productivity per cattle is expected to differ across different production systems and between industrialized, emerging, and developing regions. These projected market trends are expected to support economic and social development, but they also pose unintended environmental risks, such as increased GHG emissions (Kiers *et al.* 2008; McMichael *et al.* 2007).

There are several factors that can affect beef productivity, which is a measure of the efficiency with which beef is produced from a given population of livestock. Some of the main determinants of beef productivity include desirable genetic traits (e.g., high growth rates, good feed efficiency, and good meat quality), proper nutrition (e.g., access to a balanced and nutritious diet, and clean water), regular health care (e.g., vaccination and parasite control), suitable housing and facilities, good management practices (e.g., proper feeding and watering schedules), and suitable environment (e.g., access to pasture or forage). Lamy *et al.* (2012), for example, provided a detailed account of some these factors of the livestock sector. In absence of global level data, we assume that beef productivity improvements occur due to a combination of these individual factors.

According to the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) (FAO 2020), from 1990 to 2016, per capita beef consumption decreased from around 10 kg to 8.8 kg and beef output per head of cattle, our measure of productive efficiency, increased from 208 kg to 217 kg. However, total beef consumption increased from 53.03 thousand kt to around 66 thousand kt and total GHG emissions from beef production increased from 1.52 GtCO2e to 1.68 GtCO2e (Table 1). Such expansion is reflected in overall beef production, which has increased from around 254 million cattle head in 1990 to over 302 million in 2016. These figures demonstrate that improved productivity has not been sufficient to reduce beef production or livestock emissions due to the presence of market factors, and the tradeoff between growth and environmental performance remains.

[Table 1]

It is, therefore, important to understand the linkages between production efficiency, market mechanisms, livestock demand, and livestock emissions. Market forces must be considered when calculating the emissions reduction potential of any intervention related to improving livestock productivity. For example, from 1990 to 2016, the market price of beef has only marginally increased from US$2.44/kg to US$2.64/kg (FAO 2020)[2], while the global population has steadily increased from 5.33 billion to 7.46 billion, and global gross domestic product (GDP) per capita has increased considerably from US$8,975 to US$15,149 (in constant 2011 international $) (FAO

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[2] We calculated the market price per kg of cattle meat using FAOSTAT data on gross product value of cattle meat (constant 2004-2006 US$) and the production of cattle meats.

2020). These market factors represent an increase in the size and purchasing power of consumers, and they can create rebound effect that might undermine the emissions reduction potential of improved production efficiency.

3. Conceptual model

While the literature has extensively investigated the emissions mitigation potential of different livestock productivity-enhancing measures (e.g., Geist and Lambin 2002; Havlík *et al.* 2013; Herrero *et al.* 2013; Herrero *et al.* 2015; Herrero *et al.* 2016; Steinfeld *et al.* 2006; USEPA 2006), these studies often ignore the effect of market interactions and the resulting rebound effects (Herrero *et al.* 2016). Market forces often mediate the effect of efficiency improvements, limiting the potential reduction in livestock emissions, which may, in turn, reduce policy effectiveness or even contribute to policy failures. Using the rebound effect framework, which is widely applied in energy economics to estimate the effectiveness of efficiency improvements on reducing energy demand (e.g., Brännlund, Ghalwash, and Nordström 2007; Berkhout, Muskens, and Velthuijsen 2000; Binswanger 2001; Greening, Greene, and Difiglio 2000), we investigate whether efficiency improvements in resource use lowers the demand for cattle and, consequently, reduces methane emissions.

We formalize the theoretical model in the tradition of rebound effect models used in energy market (e.g., Berkhout, Muskens, and Velthuijsen 2000; Borenstein 2015; Chan and Gillingham 2015; Lemoine 2020). In this study, we only focus on the global beef production subindustry. The theoretical model involves defining efficiency improvements, the cost of production, the utility-maximizing level of beef consumption, and the profit-maximizing level of beef production. Common examples of efficiency improvement strategies include shifting toward mixed crop-livestock systems, livestock production intensification such as herd expansion, and transition towards climate-resilient production systems (Baker *et al.* 2013; Havlík *et al.* 2014; Herrero *et al.* 2013; Herrero *et al.* 2015; Weindl *et al.* 2015).

We assume that the beef production system has a pre-determined level of efficiency in any period t; that is, producers will only be able to enjoy the existing level of efficiency in their production process. To enable numerical calculations, we define production efficiency as beef production (kilograms) per cattle head. Therefore, efficiency is defined in terms of the transformation of inputs (cattle head) into an output (beef) and can be expressed as:

$$(1) \qquad \epsilon = \frac{B}{h} \Longrightarrow B = \epsilon h \Longrightarrow h = \frac{B}{\epsilon},$$

where B denotes the total production of beef by slaughtering h cattle heads. The ratio of B to h is defined as efficiency (ϵ). Assuming $h > 0$ and ignoring subscripts for notational simplicity, we will have $\epsilon \geq 0 \ \forall B \geq 0$.

The total cost of beef production includes all costs associated with raising cattle and applying efficiency improvements. For simplicity, we assume the cost of raising cattle to be constant, so that the total cost of beef production becomes an inverse function of efficiency; that is, higher (lower) efficiency ensures lower (higher) production costs.

Under perfect competition where markets clear at the margin, the price of beef, p, is equal to the marginal cost of beef production, which is determined by the production efficiency calculated in equation (1). Therefore, $p^* = p^*(\epsilon)$ is set at the producer's equilibrium, which can be replaced by the consumer's equilibrium to identify the market clearing level of beef production.

Let C denote the total consumption of beef and x denote a composite good representing all other consumer goods and services in the economy in any period t. The price per unit of beef is p; therefore, the total amount spent on beef consumption is pC. In contrast, at a food price index I in any period t, the total amount spent on x is Ix. For a given income y, the representative agent maximizes her utility according to:

$$(2) \qquad \begin{array}{c} \max\limits_{C,x} u(C,x) \\ s.t., \ pC + Ix = y \end{array},$$

where the utility function is strictly concave in both C and x; that is, $u_C > 0, u_{CC} < 0; u_x > 0, u_{xx} < 0$. We simplify the equation by assuming an interior solution whereby $C > 0$ and $x > 0$, such that an agent consumes positive amounts of both beef and other commodities at the equilibrium. The first order condition defining the consumer equilibrium point is:

$$(3) \qquad \frac{u_C}{u_x} = \frac{p}{I} \Longrightarrow u_C = \frac{p}{I} u_x.$$

This is the standard decision rule for the consumer's equilibrium, where the marginal rate of substitution (u_C/u_x) is equal to the price ratio (p/I). Implicitly solving for optimal amounts of beef and other commodities yields the demand functions in terms of prices according to:

$$(4) \qquad \begin{aligned} C^* &= C^*(p, I) \\ x^* &= x^*(p, I) \end{aligned}$$'

where both the demand functions follow the law of demand, i.e., $\frac{\partial C^*}{\partial p} < 0, \frac{\partial x^*}{\partial I} < 0$. In addition, cross-price effects are positive, implying some degree of substitutability between C and x, i.e., $\frac{\partial x^*}{\partial p} > 0, \frac{\partial C^*}{\partial I} > 0$.

The market clears so that we have $B^* = C^*$. Substituting the demand functions in h yields:

$$(5) \qquad h^*(p, I, \epsilon) = \frac{C^*(p,I)}{\epsilon} = \frac{C^*(p(\epsilon),I)}{\epsilon};$$

that is, the optimal cattle heads for beef production h^* is a function of both market prices and efficiency. From the demand functions, we have $\frac{\partial h^*}{\partial p} < 0$ and $\frac{\partial h^*}{\partial I} > 0$.

The direct rebound effect for productivity is defined as the effect of efficiency on the optimal level of cattle heads as $\frac{\partial h^*}{\partial \epsilon} = -\frac{C^*}{\epsilon^2} + \frac{\frac{\partial C^*}{\partial p}\frac{dp}{d\epsilon}}{\epsilon}$ which can be rearranged to determine elasticity as:

$$(6) \qquad \eta_{h\epsilon} = -1 + \eta_{Cp}\eta_{p\epsilon},$$

where $\eta_{h\epsilon} = \frac{\partial h^*}{\partial \epsilon}\frac{\epsilon}{h}$ denotes the efficiency elasticity of cattle head, $\frac{C^*}{\epsilon^2}\frac{\epsilon}{h} = 1$ denotes the direct relationship between efficiency improvement and productivity, $\eta_{Cp} = \frac{\partial C^*}{\partial p}\frac{p}{C}$ denotes the price elasticity of beef demand, and $\eta_{p\epsilon} = \frac{dp}{d\epsilon}\frac{\epsilon}{p}$ denotes the efficiency elasticity of the price of beef. The law of demand necessitates $\eta_{Cp} < 0 \; \forall p, C > 0$; however, the effect of an improvement in efficiency on price is uncertain (i.e., $\eta_{p\epsilon} \gtreqless 0$), implying that the cattle rebound effect is $\eta_{Cp}\eta_{p\epsilon} = 1 + \eta_{h\epsilon} \gtreqless 0 \; \forall p, C, \epsilon > 0$.

Emissions can be expressed as a function of cattle head according to:

$$(7) \qquad E = E(h), \frac{dE}{dh} > 0,$$

where h is derived by equation (6) so that $\frac{dE}{dh} = \frac{\partial E}{\partial \epsilon}\frac{\partial \epsilon}{\partial h} \Longrightarrow \frac{\partial E}{\partial \epsilon} = \frac{dE}{dh}\frac{\partial h}{\partial \epsilon}$, which can be expressed to determine elasticity as:

$$(8) \qquad \eta_{E\epsilon} = \eta_{Eh}\eta_{h\epsilon} = \eta_{Eh}\left(-1 + \eta_{Cp}\eta_{p\epsilon}\right),$$

where $\eta_{E\epsilon} = \frac{\partial E}{\partial \epsilon}\frac{\epsilon}{E}$ and $\eta_{Eh} = \frac{\partial h}{\partial E}\frac{E}{h}$. The emissions rebound effect is $\eta_{Eh}\eta_{Cp}\eta_{p\epsilon} = \eta_{Eh}(1 + \eta_{h\epsilon}) \gtreqless 0 \ \forall p, C, \epsilon > 0$ since $\eta_{Cp}\eta_{p\epsilon} \gtreqless 0$ and $\frac{dE}{dh} > 0$.

A calculation that does not include the effect of market forces predicts that a 1 percent improvement in beef production efficiency leads to a 1 percent reduction in the required cattle head and, consequently, total emissions will also be reduced by 1 percent. Therefore, it assumes that $\eta_{p\epsilon} = 0$ and that there is no rebound effect; hence, the full impact of the efficiency improvement is reflected in proportional reductions in the cattle head required and total emissions. Accordingly, equations (6) and (8) reduce to $\eta_{h\epsilon} = -1$ and $\eta_{E\epsilon} = -\eta_{Eh}$.

However, a calculation that incorporates the effects of the market channel assumes $\eta_{p\epsilon} \neq 0$, thereby considering the possibility of a rebound effect so that the full expressions in equations (6) and (8) hold. In this framework, the required cattle heads and rebound effects are described by $\eta_{Cp}\eta_{p\epsilon} \gtreqless 0$ and $\eta_{Eh}\eta_{Cp}\eta_{p\epsilon} \gtreqless 0 \ \forall p, C, \epsilon > 0$, respectively, which represent the direct rebound effects of efficiency improvements on cattle demand and emissions.

4. Numerical Analysis

4.1 Different scenarios

Based on the theoretical model, we conduct a numerical analysis to simulate the potential rebound effects of efficiency in the global beef production. Efficiency improvement is defined as production efficiency as beef production (kilograms) per head of cattle, as formally described in equation (1). Data on the price of beef, the food price index, livestock productivity, the production and consumption of beef, the required head of cattle, and livestock emissions come from the FAOSTAT database (FAO 2020), whereas data on GDP per capita and the consumer price index are from the WDI database (World Bank 2021). We limit our analyses to 1990 to 2017 due to the unavailability of data on some variables (e.g., the price of beef) for earlier years.

We develop four different scenarios. Table 2 reports the summary statistics for all the variables that are simulated under scenarios 1-3 whereas all simulated values are appended in tables A1 to A3.

[Table 2]

4.1.1 S1: Technological progress only

First, S*cenario 1* assumes that the market and population variables remain at their base year level. This scenario does not incorporate any market feedback and assumes that $\eta_{p\epsilon} = 0$. Technological progress will increase the efficient use of resources and, therefore, will lower the cattle heads required to meet the market demand for beef.

Current consumption is approximated by its level in 1990 according to:

$$(9) \qquad \tilde{C}_t = C_0 \; \forall t.$$

According to FAOSTAT, total global beef consumption was 53.03 thousand kt in 1990. This scenario then projects the cattle heads required to meet consumption at the level C_0 and, accordingly, the total emissions and emission intensity. The total cattle heads required, $\tilde{h}_t$, is:

$$(10) \qquad \tilde{h}_t = \frac{C_0}{\epsilon_t}, \; \epsilon_t > 0 \; \forall.$$

Equation (10) follows the assumption made in equation (9) that total consumption remains at the 1990 level. Therefore, to meet the total market demand at efficiency level ϵ_t, producers will require $\tilde{h}_t$ heads of cattle. Consequent total emissions are projected as:

$$(11) \qquad \tilde{E}_t = \left(1 + \tilde{h}_g\right) E_{t-1},$$

where $\tilde{h}_g = \frac{\tilde{h}_t - h_{t-1}}{h_{t-1}}$ is the rate of cattle production growth, which will be negative if $\tilde{h}_t < h_{t-1}$, indicating an increase in efficiency. Since $\eta_{p\epsilon} = 0$ implies that $\eta_{h\epsilon} = -1$ and $\eta_{E\epsilon} = -\eta_{Eh}$ from equations (6) and (8), $\tilde{h}_g$ also denotes the rate of emissions growth.

The projected emission intensity is:

$$\tilde{e}_t = \frac{(1+\tilde{h}_g)E_{t-1}}{C_0}. \tag{12}$$

Together, equations (9)-(12) define the scenario 1. Total consumption remains at its 1990 level, production efficiency ranges between 201.59 and 217.63 kg/head, required cattle heads ranges between 243.67 and 263.08 million, and consequent emissions between 1.28 and 1.58 GtCO2e.

4.1.2 S2: Technological progress, population, and income

Next, due to continuous research and development, it is more realistic to assume that "engineering" calculations consider market and population variables but with one-year lag. Therefore, the baseline *Scenario 2* develops the engineering effects which ignores the latest market channel and assumes $\eta_{\epsilon p} = 0$; whereas all the market and population variables remain at their last year levels.

Beyond 1990, current consumption is approximated by its past year level according to:

$$\bar{C}_t = C_{t-1}. \tag{13}$$

This scenario then projects required heads of cattle, total emissions, and emission intensity. Total required heads of cattle, $\bar{h}_t$, is:

$$\bar{h}_t = \frac{C_{t-1}}{\epsilon_t},\ \epsilon_t > 0\ \forall t. \tag{14}$$

Equation (14) follows the assumption made in (13) that the total consumption remains at the last year level. Therefore, to meet the total market demand at the productivity level ϵ_t, producers will slaughter $\bar{h}_t$ heads of cattle. Consequent total emission is projected as:

$$\bar{E}_t = (1+\bar{h}_g)E_{t-1}, \tag{15}$$

where $\bar{h}_g = \frac{\bar{h}_t - h_{t-1}}{h_{t-1}}$ is the rate of growth of slaughtered cattle heads. Similar to scenario 1, $\bar{h}_g < 0$ if $\bar{h}_t < h_{t-1}$ denoting increased resource use efficiency. $\bar{h}_g$ also denotes the rate of emissions growth. Therefore, the projected emission intensity is:

$$\bar{e}_t = \frac{(1+\bar{h}_g)E_{t-1}}{C_{t-1}}. \tag{16}$$

Equations (13)-(16) define the Scenario 2. Per-capita consumption ranges from 8.80 to 9.95 kg, whereas total consumption is calculated between 51.88 and 65.66 thousand kt. Between 253.48

and 302.78 million cattle heads will be slaughtered, resulting in total emissions between 1.51 and 1.67 GtCO2e.

4.1.3 S3: Technological progress and market responses

Scenario 3 assumes $\eta_{p\epsilon} \neq 0$; that is, it includes the market reaction and population changes in the calculation. Therefore, efficiency improvements will affect the required cattle heads and consequent emissions by changing relative prices in the market, and changes in the global population will enter the mechanism and affect total consumption and production.

Beyond 1990, current consumption is approximated according to:

$$\breve{C}_t = N_t \times \breve{c}_{t-1}(p_{t-1}^{c}, p_{t-1}^{x}, y_{t-1}) \ \forall t, \tag{17}$$

where $\breve{c}_{t-1}$ denotes per capita beef consumption in year $t-1$ as a function of three lagged explanatory variables: the unit price of beef p_{t-1}^{c}, the unit price (index) of a composite bundle x of other commodities p_{t-1}^{x}, and the per capita income y_{t-1}, assuming all other determinants of market demand remain constant. We estimate $\breve{c}_{t-1}$ using a simple OLS regression specification.

Projections of the required cattle heads and total cattle emissions are:

$$\breve{h}_t = \frac{\breve{c}_t}{\epsilon_t}, \ \epsilon_t > 0 \ \forall t \tag{18}$$

$$\breve{E}_t = \left(1 + \breve{h}_g\right) E_{t-1}, \ \breve{h}_g = \frac{\breve{h}_t - h_{t-1}}{h_{t-1}}, \tag{19}$$

where $\breve{h}_g$ will be negative if $\breve{h}_t < h_{t-1}$, denoting an increase in efficiency.

The projected emission intensity is:

$$\breve{e}_t = \frac{(1+\breve{h}_g)E_{t-1}}{\breve{C}_t}. \tag{20}$$

Scenario 3 incorporates the market mechanism according to equations (17)–(20). Total consumption is estimated to be between 51.73 and 66.05 thousand kt that requires 252.70 to 306.44 million cattle heads to be slaughtered. The resulting total emissions range between 1.52 and 1.68 GtCO2e.

4.1.4 S4: Actual outcome

Finally, *Scenario 4* uses actual data to provide a comparative analysis of the contribution of all other unaccounted factors in determining per capita consumption, total production and, therefore, the demand for beef and total emissions from beef production. Actual total consumption is between 51.73 and 66.05 thousand kt, requiring 252.70 to 306.44 million cattle heads and resulting in emissions ranging from 1.52 to 1.68 GtCO2e.

4.2 Numerical Results

We compare scenarios 3 and 4 with scenarios 1 and 2 to determine the global livestock rebound effects. Following the related literature (e.g., Berkhout, Muskens, and Velthuijsen 2000; Lemoine 2020; Saunders 2000; Sorrell and Dimitropoulos 2008; Sorrell, Dimitropoulos, and Sommerville 2009; Wang, Zhou, and Zhou 2012), the rebound effect can be calculated as the ratio of difference in changes in cattle heads under two scenarios and change in cattle heads under the baseline scenario.[3]

Figure 1 provides time series figures for these scenarios, showing the required cattle heads and livestock emissions (Panel A) and the effect of an improvement in efficiency (Panel B). Consistent with our expectations, an increase in efficiency results in a one-to-one proportional decrease in the required cattle heads in scenario 1, resulting in lower livestock emissions. However, the introduction of market factors confirms the presence of a rebound effect, where an increase in efficiency increases the required cattle head and, consequently, increases livestock emissions.

[Figure 1]

Figure 2 plots the yearly rebound effects from 1990 to 2017, Whereas Table 3 reports the average rebound effects over the period under consideration[4]. The direction and extent of the estimated rebound effects are mixed, with the evidence showing the presence of a backfire effect

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[3] This is outlined in the Technical Appendix C. As shown in equations (6) and (8), the direction and extent of cattle and emissions rebound effects depend on the direction and magnitude of market factors. These requirements are consistent with the related literature on agricultural efficiency, suggesting that while an increase in productivity can help to reduce global GHG emissions (e.g., Havlík *et al.* 2013; Jones and Sands 2013), it can only be effective if agricultural demand is inelastic (Hertel 2012).

[4] Estimated yearly rebound effects are also reported in appendix Table A6.

(i.e., $RE > 1$), a full rebound (i.e., $RE = 1$), a partial rebound (i.e., $0 < RE < 1$), and super-conservation (i.e., $RE < 0$) for different years.

[Figure 2]

[Table 3]

Cattle rebound effects calculated by comparing scenarios 1 and 3 range between -108.44 and 56.19 with a mean value of -2.35. However, when we compare the scenario 1 with actual data in scenario 4, the range becomes -30.65 to 81.27 with a mean value of 2.92. Similarly, when we compare scenario 2 with scenarios 3 and 4, ranges of rebound effects vary: [-4.14, 9.72] with a mean value of 1.03 from scenarios 2 and 3, and [-13.17, 7.09] with a mean value of 0.38 from scenarios 2 and 4.

The calculated emissions rebound effects exhibit similar patterns. For scenarios 1 and 3, the estimated livestock emissions rebound effects range between -9.91 to 10.72 with a mean value of 0.48. Similarly, the emissions rebound effects from scenarios 1 and 4 range from -5.51 to 4.71 with a mean value of 1.00. These values are way lower when we compare scenario 2 with scenarios 3 and 4: [-7.89, 11.88] with a mean value of -0.12 from scenarios 2 and 3, and [-4.06, 2.61] with a mean value of 0.27 from scenarios 2 and 4.

5. Conclusions

This article identifies the presence and extent of rebound effects in the global beef production: we confirm that productivity improvement and market forces (such as market prices, income, and population) mediate the effects of each other on beef and livestock demands and consequent emissions. Our numerical analysis confirm that efficiency improvements in global beef production at least partially offset the effects of market forces on the required cattle heads for beef production and the consequent emissions.

Our results have important policy implications in the context of climate change adaptation and mitigation. To become more effective, policy instruments aimed at reducing total livestock emissions by improving productive efficiency must account for the effect of market forces who can partially offset the benefits of such instruments. Moreover, policy instruments aiming at reducing total livestock emissions by maximizing output efficiency should be accompanied by measures for increasing adoption of greener inputs.

There are several limitations that might open avenues for future research using either extended dataset or specific case studies. For example, this article uses the case of beef production, which can be extended to other livestock products such as pork and dairy products. Second, rebound effect framework can be extended to include multiple livestock commodities to incorporate their interrelations especially in terms of competing use of resources. Third, since there exist substantial variations in efficiency, production costs and policy environment across countries, future research can investigate either specific country case studies or specific policy initiatives such as the possibility of cattle breeding with lower methane outputs (Smith *et al.* 2021). Finally, once data becomes available, an analysis across the livestock value chain can reveal relative contribution of each stage of production.

Despite these limitations, this article can serve as a benchmark for rebound effect analysis in the livestock sector at both global and regional levels. Measuring the direction and degree of rebound effects can be used to formulate effective policy tools to reduce emissions from the livestock sector. Although we only focus on the beef production system, which is a major contributor to total livestock emissions, our approach can be adapted to other livestock commodities and extended to other production systems.

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Figures

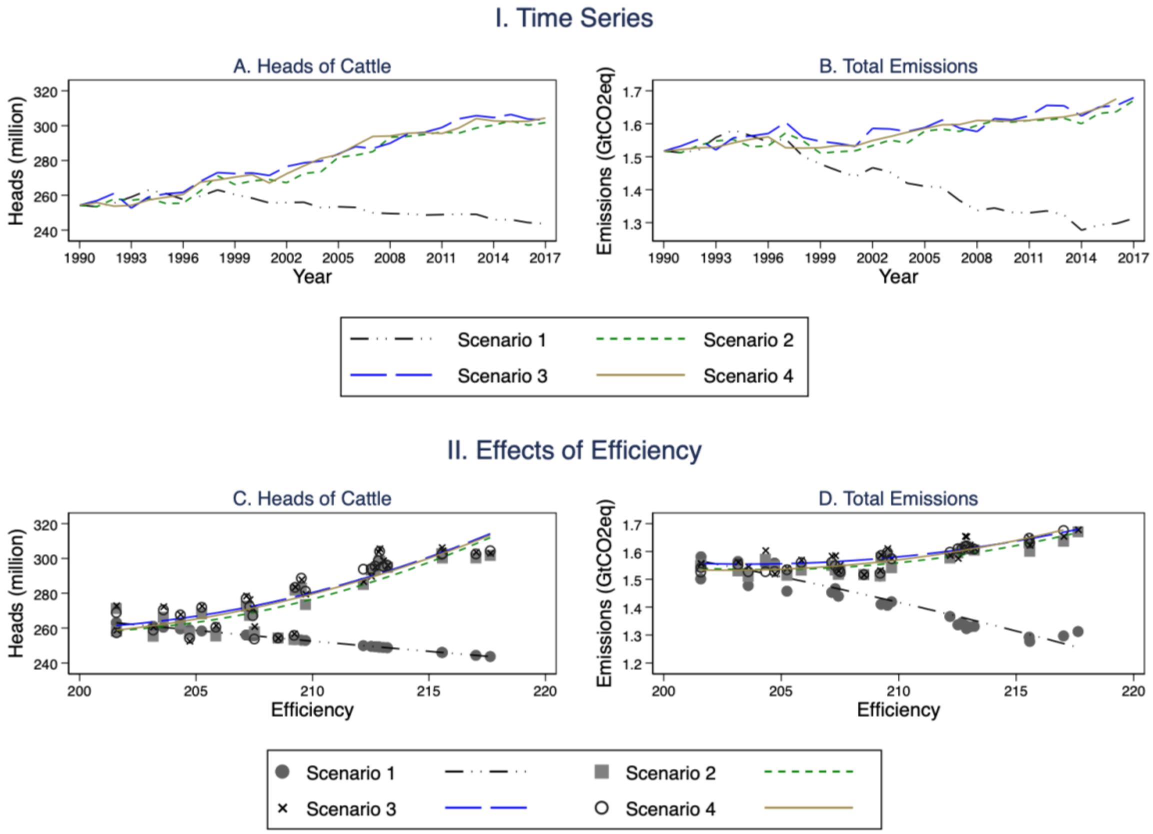

Figure 1. Alternative scenarios

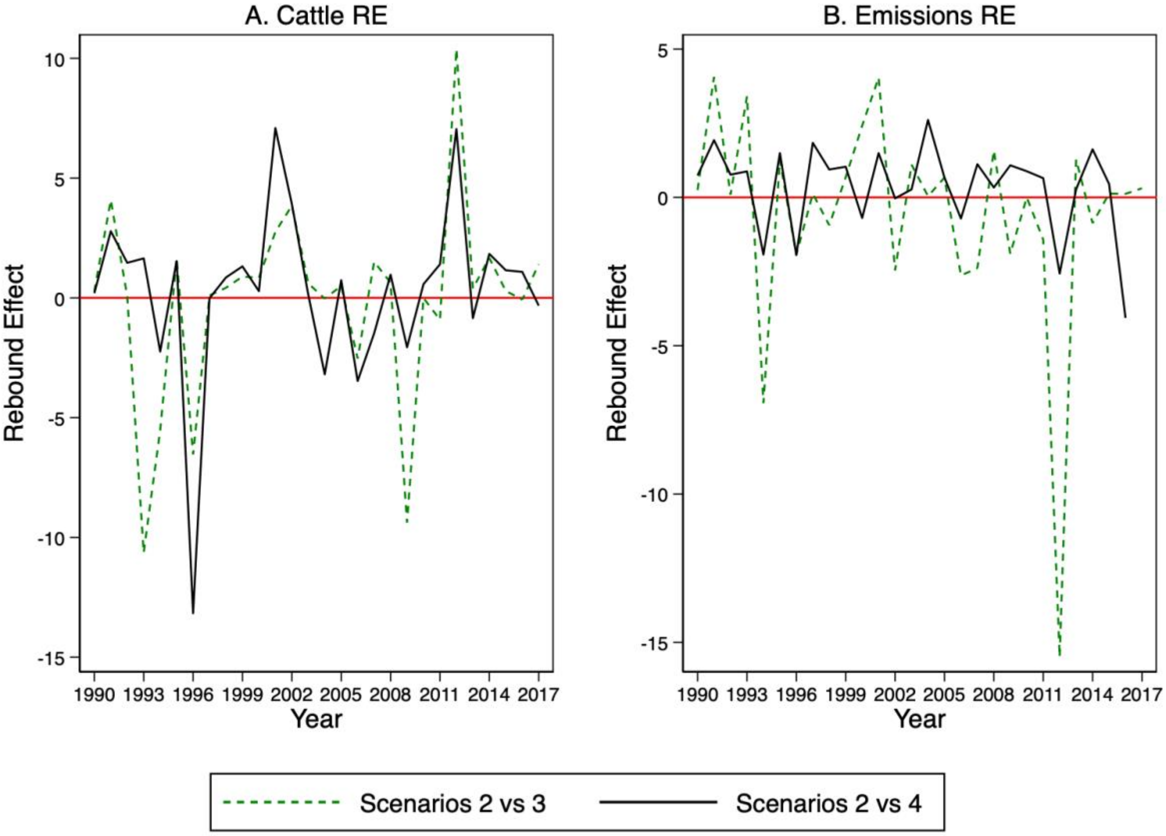

Figure 2. Numerical results of rebound effects

Tables

Table 1. Global Livestock Data

Variables	Description	Mean			
		1990	2000	2010	2016
Per capita GDP	GDP per capita, PPP (constant 2011 international ‘000 $)	8.975	10.394	13.221	15.149
Population	Global population (billion)	5.327	6.143	6.957	7.464
Cattle head	Total cattle heads slaughtered for beef (million)	254.316	271.939	296.081	302.574
Productivity	Beef per slaughtered cattle (kg)	208.518	205.242	213.216	217.015
Total emission	Total emission CO2 equivalent (Gt)	1.517	1.534	1.609	1.676
Emission intensity	CO2 equivalent emission per kg of beef	28.611	27.490	25.480	25.517
Price	Average gross value product of beef per kg	2.445	2.820	2.690	2.645
Per capita consumption	Per capita consumption (kg)	9.954	9.085	9.074	8.797
Total consumption	Total consumption (‘000 kt)	53.029	55.813	63.129	65.663

Notes: Summary statistics in Table 1 consider global level data on selected variables for the years 1990, 2000, 2010 and 2016. All data come from FAOSTAT.

Table 2. Summary Statistics

Variables	Mean	SD	Minimum	Maximum
Efficiency	209.31	4.60	201.58	217.63
Baseline Scenario 1				
Total consumption	53.03	0.00	53.03	53.03
Cattle head	253.47	5.57	243.67	263.08
Total emissions	1.43	0.10	1.28	1.58
Baseline Scenario 2				
Per capita consumption	9.18	0.31	8.80	9.95
Total consumption	58.15	4.83	51.88	65.66
Cattle head	277.52	17.52	253.48	302.78
Total emissions	1.57	0.04	1.51	1.67
Scenario 3				
Price	2.73	0.11	2.44	2.87
Nominal FPI	139.73	43.33	89.62	229.95
Per capita GDP	11.21	2.06	8.82	14.98
Per capita consumption	9.18	0.28	8.74	9.95
Total consumption	58.87	4.87	51.73	66.05
Head of cattle	280.93	17.77	252.70	306.44
Total emissions	1.59	0.04	1.52	1.68
Scenario 4				
Population	6.43	0.67	5.33	7.55
Per capita consumption	9.14	0.28	8.78	9.95
Total consumption	58.63	4.95	51.88	66.25
Head of cattle	279.76	18.14	253.75	304.41
Total emissions	1.57	0.04	1.52	1.68

Notes: Global aggregate data come from the FAOSTAT and WDI databases for the years 1990-2017. Alternative scenarios are defined by equations (11) – (20) and figure (1), and calculated using equations (21) and (23). Efficiency denotes amount of beef per slaughtered cattle (kg). Per capita GDP is in PPP constant 2011 international ‘000 \$. Global population in billions. Cattle head refers to total cattle heads for beef production (million). Total emission is expressed in CO2 equivalent (Gt). Price denotes average gross value product of beef per kg. Total consumption is in ‘000 kt, and per capita consumption is in kg.

Table 3. Average Rebound Effects

Variables	Mean	S.D.	Min.	Max.
Cattle RE				
Scenarios 1 and 3	-1.66	16.32	-62.04	27.82
Scenarios 1 and 4	2.92	17.97	-30.65	81.27
Scenarios 2 and 3	-0.12	4.04	-10.64	10.39
Scenarios 2 and 4	0.33	3.59	-13.17	7.09
Emissions RE				
Scenarios 1 and 3	0.77	2.84	-4.20	9.45
Scenarios 1 and 4	1.15	1.70	-5.51	4.71
Scenarios 2 and 3	-0.55	3.69	-15.50	4.06
Scenarios 2 and 4	0.34	1.49	-4.06	2.61

Notes: Global aggregate data come from the FAOSTAT and WDI databases for the years 1990-2017. Alternative scenarios are defined by equations (11)-(20) and calculated using equations (21) and (22).

Appendices

Table A1. Scenario 1 Values

Year	Efficiency (kg/head)	Total consumption ('000 kt)	Heads of cattle (Million)	Total emissions (GtCO2e)
1990	208.52	53.03	254.32	1.52
1991	209.21	53.03	253.48	1.51
1992	207.50	53.03	255.56	1.52
1993	204.72	53.03	259.04	1.56
1994	201.59	53.03	263.06	1.58
1995	203.16	53.03	261.02	1.56
1996	205.85	53.03	257.61	1.55
1997	204.33	53.03	259.53	1.55
1998	201.58	53.03	263.08	1.50
1999	203.60	53.03	260.46	1.48
2000	205.24	53.03	258.38	1.46
2001	207.43	53.03	255.65	1.44
2002	207.30	53.03	255.81	1.47
2003	207.15	53.03	255.99	1.45
2004	209.70	53.03	252.89	1.42
2005	209.25	53.03	253.43	1.41
2006	209.52	53.03	253.10	1.41
2007	212.18	53.03	249.92	1.37
2008	212.52	53.03	249.53	1.34
2009	212.69	53.03	249.33	1.34
2010	213.22	53.03	248.71	1.33
2011	213.03	53.03	248.93	1.33
2012	212.82	53.03	249.17	1.34
2013	212.88	53.03	249.10	1.32
2014	215.58	53.03	245.99	1.28
2015	215.55	53.03	246.02	1.29
2016	217.02	53.03	244.36	1.30
2017	217.63	53.03	243.67	1.31

Notes: All data come from the FAOSTAT database for the years 1990 to 2017. Scenario 1 is defined by equations (9) – (12) and figure (1).

Table A2. Scenario 2 Values

Year	Efficiency (kg/head)	Price (US$/kg)	Per capita consumption (kg)	Total consumption ('000 kt)	Heads of cattle (Million)	Total emissions (GtCO2e)
1990	208.52	2.44	9.95	53.03	254.32	1.52
1991	209.21	2.49	9.95	53.03	253.48	1.51
1992	207.50	2.85	9.88	53.52	257.92	1.53
1993	204.72	2.87	9.58	52.65	257.20	1.55
1994	201.59	2.87	9.32	52.04	258.17	1.55
1995	203.16	2.86	9.16	51.88	255.36	1.53
1996	205.85	2.83	9.16	52.59	255.47	1.53
1997	204.33	2.84	9.21	53.63	262.45	1.57
1998	201.58	2.84	9.26	54.67	271.22	1.55
1999	203.60	2.82	9.06	54.19	266.19	1.51
2000	205.24	2.82	9.08	55.06	268.27	1.51
2001	207.43	2.78	9.08	55.81	269.07	1.52
2002	207.30	2.79	8.90	55.40	267.27	1.53
2003	207.15	2.76	8.96	56.46	272.54	1.55
2004	209.70	2.74	8.99	57.37	273.57	1.54
2005	209.25	2.69	9.13	58.97	281.82	1.58
2006	209.52	2.68	9.06	59.30	283.01	1.58
2007	212.18	2.68	9.13	60.49	285.08	1.58
2008	212.52	2.68	9.30	62.35	293.36	1.60
2009	212.69	2.68	9.21	62.50	293.86	1.61
2010	213.22	2.69	9.15	62.88	294.90	1.61
2011	213.03	2.70	9.07	63.13	296.34	1.61
2012	212.82	2.67	8.94	62.95	295.80	1.61
2013	212.88	2.65	8.92	63.58	298.68	1.62
2014	215.58	2.64	8.98	64.73	300.28	1.60
2015	215.55	2.63	8.95	65.27	302.78	1.63
2016	217.02	2.64	8.83	65.18	300.33	1.64
2017	217.63	.	8.80	65.66	301.72	1.67

Notes: All data come from the FAOSTAT database for the years 1990 to 2017. Scenario 2 is defined by equations (13) – (16) and figure (1).

Table A3. Scenario 3 Values

Year	Efficiency (kg/head)	Price (US$/kg)	Per capita consumption (kg)	Total consumption ('000 kt)	Heads of cattle (Million)	Total emissions (GtCO2e)
1990	208.52	2.44	9.95	53.03	254.32	1.52
1991	209.21	2.49	9.93	53.75	256.91	1.53
1992	207.50	2.85	9.85	54.17	261.06	1.55
1993	204.72	2.87	9.27	51.73	252.70	1.52
1994	201.59	2.87	9.22	52.21	259.01	1.56
1995	203.16	2.86	9.23	52.99	260.85	1.56
1996	205.85	2.83	9.25	53.88	261.73	1.57
1997	204.33	2.84	9.27	54.76	268.00	1.60
1998	201.58	2.84	9.20	55.04	273.06	1.56
1999	203.60	2.82	9.15	55.48	272.49	1.55
2000	205.24	2.82	9.11	55.99	272.82	1.54
2001	207.43	2.78	9.05	56.30	271.43	1.53
2002	207.30	2.79	9.10	57.33	276.55	1.59
2003	207.15	2.76	9.04	57.72	278.62	1.58
2004	209.70	2.74	9.08	58.65	279.69	1.58
2005	209.25	2.69	9.08	59.38	283.76	1.59
2006	209.52	2.68	9.11	60.34	287.97	1.61
2007	212.18	2.68	9.08	60.88	286.93	1.59
2008	212.52	2.68	9.08	61.61	289.92	1.58
2009	212.69	2.68	9.13	62.77	295.15	1.62
2010	213.22	2.69	9.08	63.15	296.20	1.61
2011	213.03	2.70	9.04	63.68	298.93	1.62
2012	212.82	2.67	9.08	64.70	303.98	1.66
2013	212.88	2.65	9.03	65.09	305.74	1.65
2014	215.58	2.64	9.00	65.68	304.67	1.62
2015	215.55	2.63	8.95	66.05	306.44	1.65
2016	217.02	2.64	8.83	65.93	303.80	1.66
2017	217.63	.	8.74	65.99	303.23	1.68

Notes: All data come from the FAOSTAT database for the years 1990 to 2017. Scenario 3 is defined by equations (17) – (20) and figure (1).

Table A4. Determination of per capita Consumption

Variables	Scenario 3
Lagged price (beef/kg)	-1.6294***
	(0.1860)
Lagged Food Price Index (nominal)	0.0025***
	(0.0008)
Per capita GDP	-0.1604***
	(0.0176)
Constant	15.0868***
	(0.5496)
No. of Obs.	28
R-squared	0.8774

Notes: Standard errors are shown in parentheses. ***,** and * represent statistical significance at 1, 5 and 10 percent levels, respectively. For the Scenario 3, determination of per capita consumption follows equation (17), using a simple OLS regression model where the dependent variable is per capita consumption. All data come from the FAOSTAT database for the years 1990 to 2017.

Table A5. Scenario 4 Values

Year	Efficiency	Price	Population	Per capita consumption	Total consumption	Head of cattle	Total emissions
1990	208.52	2.44	5.33	9.95	53.03	254.32	1.52
1991	209.21	2.49	5.41	9.88	53.52	255.82	1.52
1992	207.50	2.85	5.50	9.58	52.65	253.75	1.53
1993	204.72	2.87	5.58	9.32	52.04	254.22	1.53
1994	201.59	2.87	5.66	9.16	51.88	257.35	1.54
1995	203.16	2.86	5.74	9.16	52.59	258.85	1.55
1996	205.85	2.83	5.82	9.21	53.63	260.51	1.56
1997	204.33	2.84	5.91	9.26	54.67	267.57	1.53
1998	201.58	2.84	5.98	9.06	54.19	268.85	1.53
1999	203.60	2.82	6.06	9.08	55.06	270.44	1.53
2000	205.24	2.82	6.14	9.08	55.81	271.94	1.53
2001	207.43	2.78	6.22	8.90	55.40	267.10	1.53
2002	207.30	2.79	6.30	8.96	56.46	272.35	1.55
2003	207.15	2.76	6.38	8.99	57.37	276.93	1.56
2004	209.70	2.74	6.46	9.13	58.97	281.22	1.57
2005	209.25	2.69	6.54	9.06	59.30	283.38	1.59
2006	209.52	2.68	6.62	9.13	60.49	288.70	1.60
2007	212.18	2.68	6.71	9.30	62.35	293.83	1.60
2008	212.52	2.68	6.79	9.21	62.50	294.09	1.61
2009	212.69	2.68	6.87	9.15	62.88	295.64	1.61
2010	213.22	2.69	6.96	9.07	63.13	296.08	1.61
2011	213.03	2.70	7.04	8.94	62.95	295.51	1.61
2012	212.82	2.67	7.13	8.92	63.58	298.76	1.62
2013	212.88	2.65	7.21	8.98	64.73	304.09	1.62
2014	215.58	2.64	7.30	8.95	65.27	302.75	1.63
2015	215.55	2.63	7.38	8.83	65.18	302.36	1.65
2016	217.02	2.64	7.46	8.80	65.66	302.57	1.68
2017	217.63	.	7.55	8.78	66.25	304.41	.

Notes: All data come from the FAOSTAT database for the years 1990 to 2017.

Table A6. Global Rebound Effects

	Heads of cattle		Total emissions	
Year	Scenario 3	Scenario 4	Scenario 3	Scenario 4
1990	0.27	0.20	0.25	0.74
1991	4.08	2.78	4.06	1.93
1992	0.06	1.46	0.09	0.77
1993	-10.64	1.65	3.41	0.88
1994	-5.53	-2.24	-6.94	-1.93
1995	1.65	1.53	1.26	1.49
1996	-6.54	-13.17	-1.93	-1.94
1997	0.10	-0.01	0.13	1.84
1998	0.42	0.85	-0.94	0.94
1999	0.89	1.31	0.68	1.03
2000	0.84	0.28	2.41	-0.69
2001	2.75	7.09	4.04	1.49
2002	3.85	3.92	-2.46	-0.03
2003	0.61	0.13	1.10	0.27
2004	-0.04	-3.19	0.04	2.61
2005	0.51	0.74	0.67	0.67
2006	-2.53	-3.47	-2.63	-0.71
2007	1.51	-1.48	-2.39	1.12
2008	0.64	0.97	1.58	0.33
2009	-9.39	-2.06	-1.90	1.08
2010	0.00	0.57	0.00	0.88
2011	-0.91	1.40	-1.42	0.65
2012	10.39	7.05	-15.50	-2.57
2013	0.39	-0.85	1.28	0.27
2014	1.67	1.84	-0.87	1.62
2015	0.29	1.15	0.13	0.45
2016	-0.08	1.09	0.12	-4.06
2017	1.41	-0.32	0.31	.

Notes: All data come from the FAOSTAT database for the years 1990 to 2017. Alternative scenarios are defined by equations (11) – (21) and figure (1). Rebound effects are calculated using equations (22) and (23).

Technical Appendix A: Derivation of (8) from (7)

Dividing both sides by $\frac{\epsilon}{h}$ yields

$$\frac{\partial h^*}{\partial \epsilon}\frac{\epsilon}{h} = -\frac{C^*}{\epsilon^2}\frac{\epsilon}{h} + \frac{\epsilon}{h}\frac{\frac{\partial C^*}{\partial p}\frac{dp}{d\epsilon}}{\epsilon}$$

Now, $\frac{C^*}{\epsilon^2}\frac{\epsilon}{h} = 1$ since $h^* = \frac{B^*}{\epsilon} = \frac{C^*}{\epsilon}$. Then, $\frac{\epsilon}{h}\frac{\frac{\partial C^* dp}{\partial p\, d\epsilon}}{\epsilon}$ can be rearranged as

$$\frac{\epsilon}{C}\frac{\partial C^*}{\partial p}\frac{dp}{d\epsilon} = \left(\frac{\partial C^*}{\partial p}\frac{p}{C}\right)\left(\frac{dp}{d\epsilon}\frac{\epsilon}{p}\right) = \eta_{Cp}\eta_{p\epsilon}$$

Technical Appendix B. Extent of rebound effects

Following table summarizes the conditions necessary for different degrees of rebound effects on the livestock demand and livestock emissions. Results are supplementary to equations (8) and (10) in the main text defining respective rebound effects.

Extent of rebound effects

	Cattle heads rebound effect	Livestock emissions rebound effect
	$\eta_{Cp}\eta_{p\epsilon} = 1 + \eta_{h\epsilon} \gtreqless 0$	$\eta_{Eh}\eta_{Cp}\eta_{p\epsilon} = \eta_{Eh}(1 + \eta_{h\epsilon}) \gtreqless 0$
Backfire effect: $RE > 1$	$\eta_{h\epsilon} > 0$	$\eta_{h\epsilon} > 0$ and $\eta_{h\epsilon} > \frac{1-\eta_{Eh}}{\eta_{Eh}}$
Full rebound: $RE = 1$	$\eta_{h\epsilon} = 0$	$\eta_{h\epsilon} = 0$
Partial rebound: $0 < RE < 1$	$\eta_{h\epsilon} < 0$	$\eta_{h\epsilon} < 0$ and $\eta_{h\epsilon} < \frac{1-\eta_{Eh}}{\eta_{Eh}}$
Zero rebound: $RE = 0$	$\eta_{h\epsilon} = -1$	$\eta_{h\epsilon} = -1$
Super-conservation: $RE < 0$	$\eta_{h\epsilon} < -1$	$\eta_{h\epsilon} < -1$ and $\eta_{h\epsilon} < \frac{-1-\eta_{Eh}}{\eta_{Eh}}$

Technical Appendix C. Calculating the Rebound Effects

Let the $\tilde{}$, $\bar{}$ and $\breve{}$ marks above variables denote the calculations under scenarios 1, 2 and 3, respectively. Therefore, $\Delta\tilde{h} = \tilde{h}_t - \tilde{h}_{t-1}$, $\Delta\bar{h} = \bar{h}_t - \bar{h}_{t-1}$ and $\Delta\breve{h} = \breve{h}_t - \breve{h}_{t-1}$ denote changes in the required cattle heads due to changes in production efficiency between times $t-1$ and t according to engineering (scenarios 1 and 2) and economic calculations (scenario 3), respectively. Corresponding changes in emissions are $\Delta\tilde{E} = \tilde{E}_t - \tilde{E}_{t-1}$, $\Delta\bar{E} = \bar{E}_t - \bar{E}_{t-1}$ and $\Delta\breve{E} = \breve{E}_t - \breve{E}_{t-1}$, respectively.

Similarly, for scenario 4, changes in the required cattle head and livestock emissions are $\Delta h = h_t - h_{t-1}$ and $\Delta E = E_t - E_{t-1}$, respectively. The rebound effect can be estimated by:

$$RE_h = \begin{cases} \frac{\Delta\tilde{h} - \Delta\breve{h}}{\Delta\tilde{h}} = 1 - \frac{\Delta\breve{h}}{\Delta\tilde{h}} & [Scenarios\ 1\ and\ 3] \\ \frac{\Delta\tilde{h} - \Delta h}{\Delta\tilde{h}} = 1 - \frac{\Delta h}{\Delta\tilde{h}} & [Scenarios\ 1\ and\ 4] \\ \frac{\Delta\bar{h} - \Delta\breve{h}}{\Delta\bar{h}} = 1 - \frac{\Delta\breve{h}}{\Delta\bar{h}} & [Scenarios\ 2\ and\ 3] \\ \frac{\Delta\bar{h} - \Delta h}{\Delta\bar{h}} = 1 - \frac{\Delta h}{\Delta\bar{h}} & [Scenarios\ 2\ and\ 4] \end{cases}$$

$$RE_E = \begin{cases} \frac{\Delta\tilde{E} - \Delta\breve{E}}{\Delta\tilde{E}} = 1 - \frac{\Delta\breve{E}}{\Delta\tilde{E}} & [Scenarios\ 1\ and\ 3] \\ \frac{\Delta\tilde{E} - \Delta E}{\Delta\tilde{E}} = 1 - \frac{\Delta E}{\Delta\tilde{E}} & [Scenarios\ 1\ and\ 4] \\ \frac{\Delta\bar{E} - \Delta\breve{E}}{\Delta\bar{E}} = 1 - \frac{\Delta\breve{E}}{\Delta\bar{E}} & [Scenarios\ 2\ and\ 3] \\ \frac{\Delta\bar{E} - \Delta E}{\Delta\bar{E}} = 1 - \frac{\Delta E}{\Delta\bar{E}} & [Scenarios\ 2\ and\ 4] \end{cases}$$