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Integrating livestock feeds and production systems into agricultural multi-market models: The example of IMPACT

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ABSTRACT

The various ways in which livestock production systems can be incorporated into economic, partial-equilibrium, multi-market models are presented, and the challenges outlined. A particular focus and illustrative case is livestock feed. Foremost among the challenges is the reconciliation of scientific understanding of livestock feed requirements and production characteristics with the available national data. Another challenge is in estimating herd structures. An economic, multi-market modeling approach is presented which has been widely used in policy analysis and advocacy, and an account is given of the necessary recent enhancements for addressing livestock.

Introduction

Economic growth in developing countries (including Latin America and the Caribbean, Sub-Saharan Africa, West Asia and North Africa (WANA), Asian developing countries, and the remaining "under-developed" countries of the world) is driving fundamental changes in the global structure of food demand. Rising incomes and rapid urbanization in these regions, particularly Asia, are creating changes in the composition of food demand. Direct per capita food consumption of maize and coarse grains is declining in many regions, as consumers shift to wheat and rice with increasing incomes. When incomes rise even further and lifestyles change with urbanization, a secondary shift from rice to wheat takes place as is already being seen in both East and South Asia – as well as an increase in the demand for livestock products. The increasing future demand for meat and milk, in particular, have been at the center of attention in many policy debates surrounding the sustainability of current dietary patterns.

Income growth in developing countries is driving strong growth in per capita and total meat consumption, leading to strong growth in the feed consumption of cereals, particularly maize. At the same time, growth in per capita meat and cereal consumption in developed countries (including Australia, Canada, Eastern Europe, EU, other Western European countries, the former Soviet Union, Israel, Japan, New Zealand, South Africa, and the United States) has slowed dramatically as these countries have reached very high levels of meat consumption in the past decades. Food consumption growth (and related requirements for animal feed) largely determines the pace at which supply growth has to also evolve to keep up with the domestic and export demand for agricultural goods. While some research has been conducted on the impact of changing consumption patterns over time on the future outlook of the world agricultural economy, relatively few authors have drawn out the implications of these consumption changes on nutrition and food security.

In order to better appreciate what the future demand for meat and milk will have on the landscape of livestock product markets, we need to have a better understanding of the widely-varied nature of livestock production systems. This need for differentiating production typologies is reflected in the discussion by van Wijk (2014). Central to any market analysis is the appropriate

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representation of the future drivers of change on the demand and supply side. While the socio-economic drivers of demand are well-understood, the supply-side drivers have not been handled as well, in the past literature, due to the way in which many models treat livestock production systems homogenously. Only recently have models of global agriculture and markets started to account for the heterogeneity of livestock systems Havlik et al. (2013) to explore the possibilities for climate mitigation (Havlik et al., 2014). In this paper, we follow the developments that have taken place in global agricultural market models like GLOBIOM (Mosnier et al., 2012), and expand our representation of the supply-side of the livestock market – particularly for ruminants – so as to better model the drivers of change that will be relevant to livestock product markets in the future.

In the paper, a characterization of the global livestock sector is first presented, outlining its importance to national income, food security and poverty indicators. Major trends in livestock production, consumption and trade are then described, and is followed by a description of how the IMPACT model is applied to agricultural policy analysis – focusing, in particular, on its recently-updated representation of livestock production, demand and trade. The simulation results of the improved IMPACT model are shown, highlighting the relevant modifications to the model's specification of the livestock sector. The paper concludes with a discussion of the results and implications for further model development and for application to livestock policy.

Background

Global livestock production, consumption and trade

Livestock production is estimated to account for up to 30 percent of the planet's land surface not covered by ice, and directly or indirectly for 70 percent of available agricultural land (Steinfeld et al., 2006). On average, livestock assets, products and activities contribute 40 percent of the total value of world agriculture – with gross domestic production (GDP) of the livestock sector accounting for more than 50 percent of agricultural GDP in industrialized countries, and 33 percent and growing in developing regions (Bruinsma, 2003; Thornton, 2010). Further, livestock production is a major employer of labor, retaining up to 1.3 billion people worldwide – most of whom are associated with resource constrained farming or pastoralist systems in developing countries where livestock typically perform a variety of economic, financial, social and environmental functions (see e.g., Thornton, 2010; Staal et al., 2009). Staal et al. (2009) estimated that more than 600 million poor livestock keepers were to be found in South Asia alone, and 300 million in sub-Saharan Africa.[1]

Global livestock production has seen marked growth in recent decades, with total meat production estimated to have expanded by more than three times from the early 1980s to year 2000 (FAO statistics). While many of the poor livestock keepers live in Asia and sub-Saharan Africa, aggregate livestock production may have been concentrated elsewhere – in Europe and the Americas. In recent years, however, livestock production has greatly expanded in China and India. Table 1 shows the average production in quantity terms of meat, milk and eggs in selected regions over a recent five year period. China currently records the highest annual production of eggs and meat, while India is the world's highest producer of milk (FAO statistics).

On a country-by-country basis (not shown in Table 1), China, the United States, and India topped the list for highest production of milk and eggs; while China, the United States and Brazil were the highest producers of meat on average over the period 2007–2011.

Table 1
Average annual meat, milk, and egg production in selected regions/countries in 2007–2011 ('000 tonnes).

Region/country	Meat	Milk	Eggs
China	74,266	40,335	27,131
India	5948	116,874	3218
Africa	15,727	41,139	2606
Asia	117,049	258,678	41,678
Oceania	5939	25,776	244
European Union	44,170	153,152	6716
Northern America	46,632	94,777	5800
World	286,382	711,682	67,802

FAO statistics online, 2013.

On the consumption side, animal source foods make up 23 percent of calories consumed per person in developed countries and 10 percent in developing countries (Bruinsma, 2003). Table 2 shows the food consumption of meat, milk and eggs in selected countries globally. While meat consumption is highest in Latin and Central America (up to 126 kg per person), the United States (125 kg per capita annually) and Europe (113 kg per person per year in Spain), it is lowest in parts of Africa and in Southeast Asia.

The statistics on trade follow a similar pattern in that developed countries account for much of the observed international trade in livestock products. This does not only apply to international but also to intra-regional trade of livestock products (for more details on intra-regional trade see Yameogo et al., 2014). In particular, Oceania, Europe and the Americas dominate world trade in livestock products.

On an individual country basis, Australia led exports of beef in the most recent year for which data was available, while the United States recorded the highest total meat exports (FAO, 2011). New Zealand and the Netherlands topped the list for exports of milk and eggs; while Italy and Germany imported the largest quantities of these commodities. Though currently accounting for a smaller proportion of the global trade in livestock products, demand for animal source commodities has been rapidly expanding in developing regions. This demand is expected to grow, – potentially doubling by 2050 – as incomes and populations in the regions rise, and with expected rapid urbanization in the next decades (Delgado et al., 1999; Steinfeld et al., 2006; Thornton, 2010).

Expansion in demand of livestock products in emerging economies may hold promise for improving incomes and livelihoods in high potential livestock production systems in these and other developing countries; and could be seen as an engine for poverty reduction amongst poorer livestock keepers (see e.g., Herrero et al., 2009; Staal et al., 2009). The thorough review of animal

Table 2
Average consumption of animal products in selected countries/regions (Kilograms/capita/year).

Region/country	Meat	Milk	Eggs
China	48.1	6.4	15.6
India	4.6	47.5	1.5
Kenya	13.7	76.7	1.3
Mali	18.6	42.6	0.7
Uruguay	126.5	131.6	9.3
Brazil	73	118.7	6.7
Spain	113.1	108.1	13.9
United States	124	117.3	14.5
World	37.9	46.4	8.0

FAO statistics, 2001.

[1] Poor livestock keeper defined as living on less than 2 United States' dollars per day.

production systems in sub-Saharan Africa by Otte and Chilonda (2002) also bears out this view. Further, increased consumption of animal source foods, a possible outcome of (their) increased participation in livestock production activities, could improve the diets, nutrition and health of vulnerable populations (see e.g., Speedy, 2003; Dror and Allen, 2011).

Quantitative analysis

Key elements of modeling livestock

Micro-level perspective

There are a number of important ways in which the household dimensions of livestock production and consumption can be brought out within a quantitative modeling framework. From a micro-level perspective, the supply side of livestock production would capture the essential inputs of labor (household or paid) and feed – which would be sourced from local forage, household farm residues or waste, or even purchased as an input. For those resources which are sourced from the household – such as labor – there would be an implicit price that recognizes the limiting scarcity of that resource within the household economy, and the tradeoffs between its use in livestock production and other alternative uses. For those goods which are purchased, the budget constraint of the household captures the monetary tradeoff between the expenditure on those goods, and possible expenditures for other types of household consumption. Household-level data are often not detailed enough to identify a relationship between animal feed intake and per-animal productivity, that can be used in quantitative modeling of the supply-side. Therefore, we use a biophysical model of livestock productivity that is better able to make the linkage between feed intake and per-animal yield of meat and milk. This is explained in further detail, later.

On the demand side, the micro-level household perspective would be able to capture the consumption of livestock products that are sourced directly from the household's own production, versus those quantities that are purchased from the outside market. This is a particularly important dimension of 'auto-consumption' that is relevant for many rural, pastoral households that source a good deal of protein from their own production, and who may have some additional surplus that can be marketed for additional income. Unless primary data is collected on the consumption and expenditure patterns of household, with the level of detail that can capture the quantities of food and non-food items consumed from own- or purchased sources, it may not be able to capture this aspect very well. At the micro-level, a rigorous analysis of consumption response can be carried out, using the price and quantity data that would be obtained from consumption and expenditure surveys, so that a more complete demand system can be derived, which reflects the regularity that one would expect from micro-level, economic theory of the consumer. When dealing with livestock products, a multi-stage budgeting approach – where separability is assumed between food/non-food and meat/non-meat categories – can be imposed, so as to reflect the variation between expenditure categories.

Macro-level perspective

In order to look at the more macro-level dynamics of livestock market interactions, some details that would otherwise come out from a more micro-level, household analysis have to be suppressed, by necessity. There are some key elements that could be retained, so as to better inform the quantitative analysis – both on the supply and demand side. On the supply-side, the more aggregate representation of livestock production cannot capture all aspects that could be explored at the household-level – however the distinction between 'industrial' and 'back-yard' livestock operations help to draw a distinction between the more intensive sectors which perform more like a profit-maximizing firm, versus those sectors that are more constrained by the limits of inputs at the household-level. Bahta and Malope (2014) include more details on different livestock keeping household types in their study, which are not suitable for macro level modeling (yet). On the demand-side, the share of production that is directly consumed by households, rather than being marketed as surplus, can be calculated from data obtained at the household-level. In terms of specifying the response of consumer demand to price and income changes – this can also be calculated from the appropriate consumption and expenditure data that could be obtained from the household-level.

In addition, microeconomic analyses of farm or household level data, useful for unraveling underlying behavior, could provide the framework for robust mathematical representation of demand and supply behavior of economic actors captured in the higher-order models. van Wijk (2014) points out how agent-based models can be used to provide a bottom-up approach to representing producer-level behavior in aggregate outcomes – with the associated computational challenges. However, the database on livestock in developing countries, particularly in sub-Saharan Africa has historically been fragmented and inaccessible, somewhat limiting potential for livestock quantification modeling. Efforts that improve the livestock data base (e.g., Otte and Chilonda, 2002) or catalyze achievement of the same (e.g., Pica-Ciamarra et al., 2014), by addressing perhaps the most limiting factor, improve the development and application of quantitative models for the analysis of pro-poor livestock policy, research and investments for development.

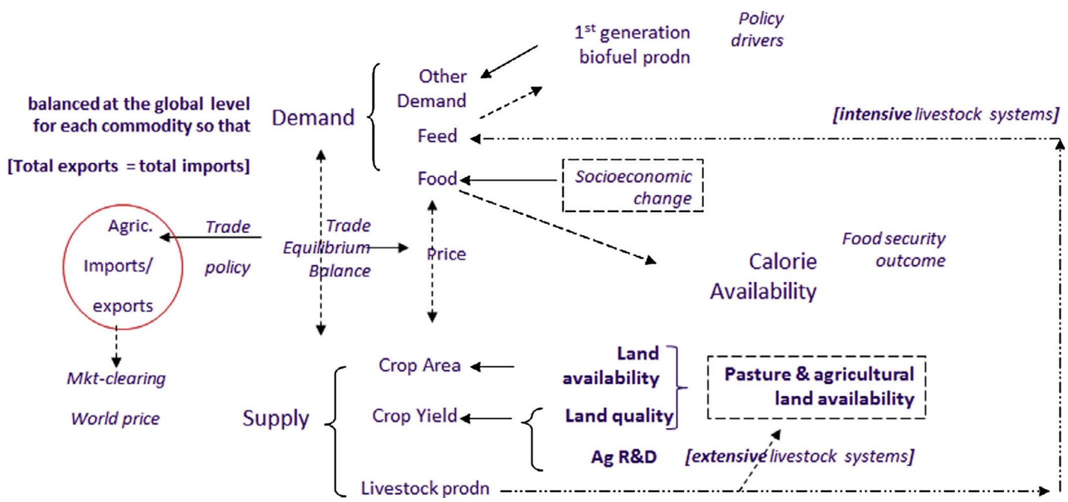
Forward-looking analysis of livestock markets

The livestock models that are the basis of the forward-looking or futures analyses make use of quantitative modeling methods, and of highly aggregated data on productivity and production, consumption and demand, and market and trade. Farm, household and other survey data can play an important role in informing appropriate aggregation of the data used in these models, and can further provide useful information for estimating the distribution of outcomes or effects of the global changes that are more directly measured by the models.

The links between livestock production activities on the one hand, and income, nutrition and environmental outcomes on the other have been much investigated, including in forward-looking analyses (e.g., Delgado et al., 1999; Steinfeld et al., 2006; Nelson et al., 2010). Nonetheless, such issues as the capacity, roles and implications of livestock production systems in developing countries to respond to future demand from rising incomes and populations remain largely underexplored. Partial-equilibrium agricultural sector models that offer a detailed description of the agriculture sector, computational ease, mathematical tractability and a minimal level of data requirements (compared, for example to computable general-equilibrium models) may be quite desirable for addressing questions of this nature on a regional or even multi-country scale.

The schematic below (Fig. 1) illustrates the key dimensions of livestock supply and demand that we wish to capture in this analysis.

Our quantitative scheme links both the supply and demand of crops and livestock together, as there are important linkages in terms of feed usage, land usage and common drivers of consumer demand – namely population and income growth. By taking into account the consumption of both crop and livestock products, one is able to ascertain the total intake of calorie, protein, fats, etc., that is necessary to determine overall food availability and its implications for nutrition and overall food security.



Source: Authors

Fig. 1. Key model linkages for livestock. *Source:* Authors.

In order to operationalize these relationships, we use a global, economic, multi-market equilibrium model – the IMPACT model of IFPRI – that is described in the following sub-section.

The IMPACT model

For this analysis, we use the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), which is a model that has been widely applied to global projections on agricultural supply, demand and trade – as well as for ex-ante assessments of the long run impacts of changes in drivers of agricultural production such as technological and climate change.

IMPACT is a widely used global food policy model developed at the International Food Policy Research Institute (IFPRI). At the heart of the model, set in the framework of a partial equilibrium economy, is the definition of reduced form supply and demand equations that characterize production and use of a number of internationally-traded primary agricultural commodities. van Wijk (2014) describes IMPACT as a top-down approach to representing production behavior, along with other similar macro-level, multi-market models. Crop production is simulated in the model for 281 food production units that are intersections of (115) economic regions and (126) river basins globally. 45 internationally traded commodities covering grain, legume, root and tuber, fruit and vegetable, and oil seed categories are grown on rain-fed and/or irrigated land, while beef, milk, lamb, eggs, poultry and pork constitute livestock commodities in the model.[2] A water simulation module ensures balances in water demand and supply in key economic sectors, globally and within regions. Endogenous world market prices for individual commodities uphold market-clearing assumptions imposed on the model, while income and population growth are defined exogenously. Results from the model runs include demand and production projections, from which indices of welfare such as child nutrition status can also be calculated. Examples of applications of the IMPACT model can be found (for general application) in Rosegrant et al., 1999, 2001, Nelson et al., 2010; IFPRI, 2012 and (for livestock-sector specific applications) Delgado et al. (1999), McDermott et al. (2013).

Since its inception and early applications in the 1990s, the model has undergone various modifications to improve its usefulness for policy analyses and projections. While the number of crops, and uses for these crops, has been greatly expanded in the model in recent years, the treatment of livestock production and feed demand remained virtually unimproved. One reason for this was a lack of system-specific livestock quantity and production data on a global level. Recent work by scientists at the International Livestock Research Institute (ILRI) and the International Institute for Applied Systems Analysis (IIASA) make it possible to move the IMPACT model toward the simulation of system-specific production and feed demand. Until its current enhancements, the model did not account for any variability in the agro-ecological systems supporting livestock production, specifying production as homogenous across systems within each country. As such, it did not lend itself to exploring how shifts within systems, i.e. extensive grazing to more intensive systems, will affect global livestock production, feed demand, and even crop production.

We here present the IMPACT model, limiting our representation of livestock and livestock feed relationships to those most relevant to the analysis that we will do within this paper. A complete description of the model is available in Rosegrant et al. (2012). We start out with describing the way in which the IMPACT model has been handling the livestock sector prior to the improvements that we will describe in the rest of the paper. Mathematical representation of animal numbers, unit production and volume of livestock production in IMPACT are as in Eqs. (A1)–(A3) in the Appendix A. Livestock feed demand is captured in Eq. (A4). Important to note from the equations is that the numbers of animals slaughtered (Appendix A, Eq. (A1)) is a composite function with an endogenous price-driven component and an externally-defined growth rate factor. Production per head (Eq. (A2)) on the other hand is entirely driven by a yield growth rate defined outside of the model specifications. The economic unit of production for livestock commodities as represented in the IMPACT model is the country. Livestock feed demand within this economic unit is responsive to volumes of livestock production, market prices of feed crop commodities and fixed feed conversion and efficiency improvement factors.

Representation of trade

Trade is represented in the IMPACT model as a function of domestic production, domestic demand and stock changes on

[2] The livestock enhancements reported in this report were based on the IMPACT model version available for use early 2013. The structure of this model is undergoing changes to amongst others, re-define regional and river basin boundaries (increasing the number of FPUs), and expanding the number and uses of crop commodities. Work starting in the fourth quarter of 2013 will update the livestock enhancements discussed here for compatibility with the version of IMPACT under development.

country level. Global net trade of each commodity equals zero for the international market to be cleared and the world prices adjust accordingly. Tariff and non-tariff barriers are not considered at this stage. In the current version of the model, traded commodities are treated as homogenous, which means that consumers do not differentiate between imported and domestic products. The importance of diversification and sophistication of livestock products for African countries, to improve intra-regional and international trade in the future, is emphasized by Yameogo et al. (2014).

As regional and international markets become increasingly connected through trade, consideration of barriers to trade, tariff and non-tariff barriers, is an important factor for future developments of the model. Non-tariff barriers in form of diseases, i.e. food and mouth epidemic regions vs. non-epidemic regions, quality standards, labeling regulations, quarantine procedures, import licenses, etc. are relevant features of the sector and play a critical role especially for developing countries that are trading processed and unprocessed livestock products. However, such characteristics are difficult to model, especially within a multi-market model, from a technical perspective, and in regard to data requirements. Little et al. (2014) discuss the importance of incorporating non-tradability when presenting rural pastoralists, which we also do not capture in IMPACT. One concrete first step toward improving the livestock module of the IMPACT model will be to incorporate disease threats, i.e. by separating foot and mouth disease epidemic regions from regions that are not affected by the disease. Disease threats vary by location and production system, and it would require detailed and reliable data to enhance the model in this way (see for example, Fadiga and Katjiuongua, 2014). Trade has not been the main focus of the current round of improvements of the livestock sector in IMPACT, but future amendments will consider more detailed analysis and quantification of intra-regional and global trade effects.

Key improvements to the IMPACT model

In this paper, we focus on the ruminants in the livestock sector, given the fact that their supply response is made more complex, compared to monogastrics, due to the nature of their herd dynamics. In IMPACT, we treat non-ruminants as 'annual' production activities, whose dynamics do not carry over into the next period, the way that herd growth dynamics due for ruminants. Therefore – we draw a clear dichotomy between the supply response of ruminants and non-ruminants, in the model. We also draw a distinction between the feed characteristics of ruminants and non-ruminants, primarily in terms of diet. The classification of livestock systems obtained from FAO sources in the form of gridded animal populations that disaggregate ruminant and non-ruminant production, show the dietary differences across various agro-ecologies. Whereas there is a high concentration of non-ruminants in the more intensive 'urban' classifications, or in the 'other' categories – we see large numbers of ruminants in more grass-fed extensive systems. Therefore, the underlying gridded data for livestock populations provides a basis for drawing a clear difference between how ruminants and non-ruminants are fed, in a similar spirit to what van Wijk (2014) suggests. But the fact that we only have biophysical modeling inputs for ruminants, limits the degree to which we can draw out the implications for feed on non-ruminant productivity.

A key challenge to expanding the model's capacity for addressing livestock policy modeling more completely, lies in accounting for animals in the herd that are not slaughtered or milked within the year (or other simulation period). This omission of the 'follower herd', reinforced by the tendency for national statistics to neglect total herd numbers in favor of reporting production, possibly leads to the overestimation of the capacities for local livestock feed systems to sustain planned or other expansions in countries' livestock sectors. Another key challenge to incorporating livestock production systems into market equilibrium models in general is the fact that whereas the allocation of animal feed can be modeled within a price-driven, static, equilibrium framework – the growth of ruminant herd numbers requires a more dynamic framework in which the stocks of animals have to be distinguished from the 'flow' of new animal births, deaths and offtake for slaughter.

To improve the model's consistency with underlying biophysical realities and to enhance its application to livestock-related policy analyses, a number of changes were implemented to how livestock production and feed demand are represented in IMPACT. We focused on five salient features of the model's livestock sector considered to pose the greatest limitations: (1) homogenous representation of livestock production within countries (2) omission of livestock feed sources such as rangeland grasses and crop residues (3) non-responsiveness in yields to changes in biomass amounts and nutritive value of livestock feeds (4) non-accounting of replacement or follower livestock animals in herd inventories or feed demand aggregations and (5) price-responsive expansion in supplies of livestock commodities that do not factor in feed availability constraints on growth potential.

The model enhancements that were implemented to address the outlined limitations centered around the expansion of livestock feed rations to include other sources of feed biomass such as crop residues and (grazed or cut-and carry) pastures, the re-specification of meat and milk productivity as feed-responsive yield functions, and the incorporation of constrained herd growth dynamics in the model supply behavior. The relevant characterizations of the model both before and after the updates we implemented are shown in Table 3.

The changes described in the table above represent a major shift in the way in which livestock are represented in the model, and allow IMPACT to address a much wider range of issues around livestock-related policy and drivers of change.

Systems disaggregation of livestock production

Before even making any changes to the equations of the model, we had to adapt the model database to account for the heterogeneity in livestock production systems across the world. As is described in the first row of Table 3, above, the previous version of IMPACT treated the livestock types as being homogenous across regions, and did not reflect the variation in production characteristics that is captured in the livestock systems definitions embedded in the gridded data provided by FAO (Robinson et al., 2011). The most critical improvement to the modeling framework is in the disaggregation of the supply-side of the livestock market by production systems. Just in the same way that the supply of crops is disaggregated between irrigated and rainfed systems, in IMPACT, we have also disaggregated livestock production systems, given the implications for both feed demand and future supply response.

Country-level livestock production is disaggregated in the model by creating new indices of food production unit (FPU)-based livestock production systems (LPS), designating production unit and livestock system specificity (see Eqs. (A9) and (A10); and (A13)–(A15) in Appendix B). Appropriate system-specific parameters were derived for the modified supply response equations, from econometric estimation of baseline data on livestock numbers, yields and feeds, and other methods.[3]

Livestock systems disaggregation in our enhanced livestock sector is based on work by Sere and Steinfeld (1996) which classified livestock production into 11 global systems that account

[3] See subsequent sections for details on changes made to the structure of the numbers and yield supply functions, and parameterization of the modified functions.

Table 3
Original specification of livestock in IMPACT and key changes to model.

Original specification	Updates to model
Supply response is relatively homogenous within countries	Livestock supply disaggregated by system types (intensive/extensive)
Livestock feed basket composed only of internationally-traded feeds (mostly coarse grains and meals)	Pasture grasses, crop residues and occasional feeds added to livestock feeding possibilities
Yield is exogenously determined, and does not respond to quantity or quality of fed rations	Meat and milk response functions are endogenous, responding to changes in feed quantities and nutritive values
Total herd size includes milk-producing and slaughtered meat animals only	Total herd count includes replacement and/or follower herds in dairy and meat production
Animal productivity only indirectly affected but not affected by feed availability through price effects	Explicit feed-availability constraints imposed on animal productivity

for differences in agro-ecological zones, management practices and land use.[4] That early work has seen a number of extensions, including the application of analytical mapping tools to the definition of spatial boundaries; and the application of statistical and mathematical programming tools to the calculation of system-specific distributions of livestock populations and production levels (e.g., Kruska et al., 2003; Robinson et al., 2011; Herrero et al., 2013). The Sere and Steinfeld (1996) classification and its variations have also been applied to the evaluation of livestock development options; including the assessment of biomass availability to meet expanding regional livestock feed demand (Herrero et al., 2009).

The systems classification proposed for use in the current enhancement to the livestock representation of IMPACT collapsed the original 11 classes into eight systems that are practical for the current context (see Appendix A). Grassland-based systems are as defined for Temperate and Tropical Highlands; Humid and sub-Tropics; and Arid and semi-Arid ecological zones. Mixed systems on the other hand, while preserving their sub-division according to ecological zones, are composite of the irrigated and mixed crop-livestock systems in the Sere and Steinfeld (1996) classification. This is without loss of applicability as far as livestock system simulation is concerned, as the potential effects on livestock of differences in seasonal water availability (as brought on by irrigation) are captured in the model through crop-livestock interactions that occur at higher aggregation.

A further description of the key underlying data that describes the livestock systems is given in Appendix C.

Endogenizing livestock productivity response

Livestock production was quantified using econometric equations that link per unit quantities of milk and meat produced in the livestock production unit to bundles of feeds (see Eqs. (A5) and (A6) in Appendix B). An animal nutrition model, *Ruminant* was applied to providing inputs for economic modeling of the biophysical process.[5] The model and derived equations are relevant for livestock ruminant animals and products only. The simulations are based entirely on biological feasibilities and do not take into consideration market prices. In addition, non-nutrition factors like animal genetics and livestock management that nonetheless influence yields are not explicitly handled, neither are the effects of heat or water stress on animal production. We however argue for the appropriate application of this software to the current modeling exercise on the basis that, endogenous prices determine the allocation of aggregate marketed feed amounts (grains and concentrates) in IMPACT between individual components of the grain and concentrate feed category. Further, region and livestock-systems specifications of our reduced-form equations account for agro-ecological and regional differences that to some extent determine global variability in genetic material and management options applied.

The functional relationships used to represent livestock yield in the revised IMPACT model were selected against flexibility, parsimony, interpretation and interpolation criteria relevant to the context (Griffin et al., 1987). Two functional forms, the Log-linear and Quadratic, were finally selected following a data-driven process.

Improving the representation of livestock numbers growth

An elaborate livestock herd dynamics modeling exercise was not attempted. Instead, a few important changes were implemented to improve the accounting for animal herds, to better define feed demand and availability balances, and to assess the potential for expanding livestock production under localized feed-constraint conditions. New variables were created to simulate the presence in the herds of follower ruminant animals - a feature important for capturing multi-period stock and flow relationships characteristic of livestock ruminant systems (in contrast to annual or bi-annual crop production) but largely ignored in national statistics. Equations (7 through 10 in Appendix B) model the revised calculations for total ruminant livestock numbers.

Observed livestock numbers in the current period are net of the previous year's stocks and animals removed from the herd through slaughter. Region-specific growth rates were applied to the net total livestock numbers over time. These growth rates represent net birth rates and are derived from historical data on livestock herd stocks. Total ruminant numbers within a country are a composite of animals found in dairy, meat and follower livestock herds. Note here that the meat herd includes those animals that are slaughtered for meat in the current period, and animals left standing for slaughter sale on a later date.

Changes in the allocation of livestock feed and characterization of animal diets

To reconcile the model demand for feed grains with the now re-defined equations on livestock yields and animal numbers, adjustments were made to how total demand of marketed feeds is calculated and allocated in IMPACT. These are shown in the Appendix (B, Eqs. (A12)–(A15)). Country total consumption of marketed feeds is allocated across feed crop commodities using a price-responsive allocation mechanism, with the share of marketed feeds derived as a function of the effective feed prices and estimated feed price elasticities.

The feed ration choices or feeding regimes observed in the baseline data are in the model maintained throughout the simulation periods by applying the same livestock yield response equations (estimated using the data and appropriately calibrated in the base year to FAO national statistics on production) to individual FPU-based livestock production systems over time. An underlying assumption of this procedure is that the feeding regimes are in themselves a reflection of prevailing environmental and natural

[4] Grassland based (Temperate and Tropical Highlands; Humid/sub-Tropics; Arid/semi-arid); Mixed Rainfed (Temperate/Tropical Highlands; Humid /sub-Tropics; Arid/semi-arid); Mixed Irrigated (Temperate/Tropical Highlands; Humid/sub-Tropics; Arid & semi-arid); and Urban or Landless.

[5] A full description of *Ruminant* model and the processes it simulates is available in Herrero et al., 2013.

resource constraints on feed possibilities, and of cultural preferences, and exhaust/optimize possible feeding options in a location. An implication of this for the model's behavior is that more or less quantities of a feed (that is already in use) may be utilized to affect yields, but no new feeds will be introduced into (or current feeds taken out of) the possibilities set of livestock feed types. As such, livestock systems may not 'switch' their species/products-specific feeding rations in response to economic, environmental or other factors, although the site of production itself may shift in response to local feed resource availabilities.

Finally, a constraint on livestock feed supply was introduced to recognize agro-ecological limits to livestock (non-internationally traded) feed availability.

Further details of the underlying data that enabled us to characterize the feeding patterns across the livestock systems represented in IMPACT, is given in Appendix D.

The consumption side of the model. It should be noted that much of the work that has been done on IMPACT has focused on the representation of supply of livestock products – whereas no changes have happened on the consumption side. This choice was based upon a prioritization of topics that the research team wanted to cover – such as climate change – which demand a much better treatment of the supply side of the model than was there. The consumption side could be expanded further, as well, especially with regards to the socio-economic strata of consumers. Given the global and fairly aggregate nature of the model, it would not be feasible to insert the level of socio-economic detail that is present in some of the micro-simulation modules of economy-wide models – which might consider urban and rural consumers of different income strata. At a minimum, the consumption of goods could be differentiated between urban and rural demands, provided there are sufficient data to disaggregate the price and income elasticities of demand for all commodities and all products (over all regions – or at least a significant subset). The disaggregation of food demand parameters by Seale et al. (2003) provide a starting point for this work – but would be fairly involved, in order for this to be done in a consistent way across all the commodities that IMPACT covers. It would certainly add to an understanding of the way in which urbanization might drive the change for livestock products – which is one of the food categories which are strongly affected by changes in socio-economic status.

In poorer countries, in which livestock keepers might be in relatively marginal areas, the choices that these livestock-keepers make between production and consumption of livestock products are strongly linked, and make products like milk a 'home good' that is mostly consumed within the households, with occasional sales of surpluses to the market. Little et al. (2014) also touch on this issue. This kind of non-separability between consumption and production is a hallmark of the household farm type models that De Janvry et al. (1993), among others, have examined in detail, within the context of developing countries. It is beyond the scope of our model to incorporate a 'household-farm' production system in a more explicit way, given the global scope of the model, and the additional data that would be required to identify the key parameters of consumption and production that would characterize such a system. Such type of characterizations have been done within smaller, country- or region-focused models, in which there is often an explicit optimization of household utility for those agents that make joint decisions on consumption and production. The FFSIM model of Louhichi et al. (2013) is an example of this, but is much more micro-focused than a global model like IMPACT. The authors do recognize the importance of these questions, but leave it for a different class of models to address them.

Summary of key changes to the model

To give the reader a clearer understanding of what these various enhancements to the model structure – as described in Table 3 and the following sub-sections – mean, we juxtapose the key model components of the livestock sector "before" and "after" the improvements described, in Table 4 below.

Table 4 gives a quasi-mathematical representation of how changes in animal numbers, productivity and the allocation of livestock feed are handled in IMPACT both before and after the model enhancements. The essence of the model changes, as captured in the table, are:

(1) To make the numbers growth modeling less reliant upon price-driven response (as would be the case for an annual crop) – and more dependent upon demographic determinants. In essence, the slaughter response is the only price-driven adjustment to herd numbers that occurs within the model. The updating of animal numbers, between periods,

Table 4
Animal number, productivity and feed allocation in IMPACT before and after changes.

	IMPACT before improvements	IMPACT with livestock improvements
(1) Animal numbers response[a]	$N_i^{milk/meat} = \alpha_i \cdot \prod_{j \neq i} (P_j)^{\varepsilon_j} \cdot \prod_k (P_k)^{\mu_k}$	$N_{i,t+1}^{total} = \left(N_{i,t}^{total} - SL_t\right) \cdot \left(1 + g_{i,t}^{numb}\right)$ $SL_t = g(P_t^{meat}; \chi) \quad N_{i,t}^{total} = N_{i,t}^{meat} + N_{i,t}^{milk} + N_{i,t}^{fllwr}$
	With price elasticities for animal products (ε_j), and with respect to feed prices (μ_k)	With sub-groups $\left(N_{i,t}^{meat}, N_{i,t}^{milk}, N_{i,t}^{fllwr}\right)$ occurring in proportions consistent with data, and price responsive slaughter SL_t
(2) Animal productivity response[b]	$Y_{i,t+1}^{milk/meat} = Y_{i,t}^{milk/meat} \cdot \left(1 + g_{i,t}^{yld}\right)$	$Y_i^{milk/meat} = f_{yld}\left(\left\{Fd_k^i\right\}_{k=diet}; \beta_i\right)$
	With fixed growth rate over time $g_{i,t}^{yld}$	With $\left\{Fd_k^i\right\}_{k=diet}$ reflective of animal diet regime, and vector of animal-specific characteristics β_i
(3) Feed demand relationships	$TotFeed_k = \alpha_k \cdot \sum_{anim}\left(FR_k^{anim} \cdot Q_{anim}\right) \cdot \prod_{k'} (P_{k'})^{\sigma_{k'}}$	$Feed_k = \theta(P_k, \mathbf{P}_{k'}) \cdot MktFeed_k \quad \theta(P_k, \mathbf{P}_{k'}) \leq 1$ $MktFeed_k = \sum_i Diet_i^{k \subset MktFeeds} \cdot N_i^{total}$ $nonMktFeed_{k'}^{req} = \sum_i Diet_i^{k \subset nonMktFeeds} \cdot N_i^{total}$
	With feed ratios FR_k^{anim} with respect to animal production Q_{anim}, and elasticities of feed price $\sigma_{k'}$	Where non-marketed feeds are limited by availability and may not achieve requirements ($nonMktFeed_{k'}^{req}$)

[a] To maintain consistency with the notation seen in the Appendices, we denote animal numbers by "N", and use "P" to denote prices, where as "g" is used for growth rates that are applied from year-to-year.

[b] To maintain consistency with notation elsewhere, we use "Y" to denote per-animal yield or productivity.

according to the net birth rates is done outside of the overall equilibrium solution.
(2) The yield response is more closely tied to the model's equilibrium-driven feed allocation of marketed feeds, and is not purely an exogenously specified process.
(3) The allocation of feed goes beyond just the marketed coarse grains and meals – but also extends to non-marketed grasses, crop residues and other occasional feeds. This enables the environmental impacts on livestock to be better captured through the availability of key feedstuffs, in a much better way than before.

To the extent that differences between breeds can be captured in the biophysical models of livestock production, such as the *Ruminant* model (Herrero et al., 2013), we could use the vector of animal-specific characteristics (β_i) to differentiate the productivity response of animals, in row (2) of Table 4. If there were to be a disease-driven shock to the productivity of the herd, this vector could also represent the difference in how various breeds might cope with and recover from the shock. Since the *Ruminant* model focuses more on the feed-productivity dimensions, it does not provide an explicit way in which to model the impacts of animal diseases. Therefore, no quantitative representation of these effects can be given in this paper.

In the following section, we will show the difference that these model enhancements make to the performance of IMPACT – both in terms of the baseline projections, as well as the response to scenario-driven shocks.

Model results

We now describe how the model improvements described in the previous sections enable the IMPACT model to better capture livestock production response, across the systems of livestock production that are relevant to different parts of the world.

Baseline projections

Below we show the levels of livestock meat (Fig. 2) and milk production (Fig. 3) for key countries of the world.

Where the growth in beef and mutton meat is much more dynamic in East Asia (China), compared to South Asia (India), and where the production in Latin America (Brazil) is much higher than either Asian region, and is more dynamic than the production levels in North America (USA) – exceeding the US production value by 2030.

For milk products, the production levels in South Asia (India) far exceed those production levels in any of the other regions, and are seen to be much more dynamic, as compared to China or Brazil (Fig. 3). The production levels in the US remain fairly stable over the period, as compared to Brazil, which grows slowly over time.

To appreciate the underlying animal numbers dynamics, which are behind these results, we show the numbers of large ruminants in the various broad animal classes for China, below (Fig. 4).

Here, we see the break down between those animals that are milked ('milk'), those that are slaughtered ('meat') and those in the 'follower' herd, which is comprised mostly of juveniles, subadults and breeding stock. For China, the numbers increase across all categories, with the total large ruminant herd reaching over 300 million head by 2030.

In Fig. 5, below, we see the breakdown of small ruminants in China, and notice that the numbers of milk-producing small ruminants (i.e. goats) is very small compared to the meat-producing and following herd.

These projections can be compared to those of India, which show (as in Fig. 6 below) a much more dynamically-growing milk-producing segment of the large ruminant population, compared to the numbers of animals producing meat or in the follower herd.

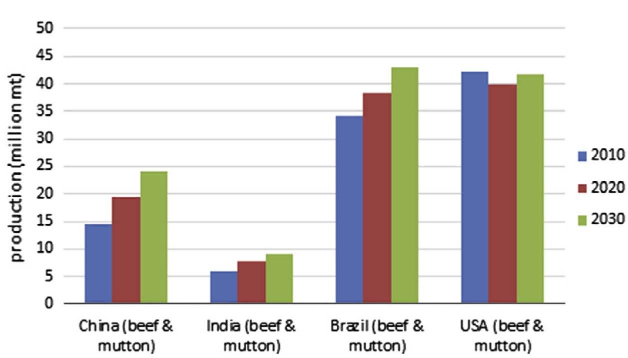


Fig. 2. Beef and mutton production for key countries. *Source:* IMPACT model simulations.

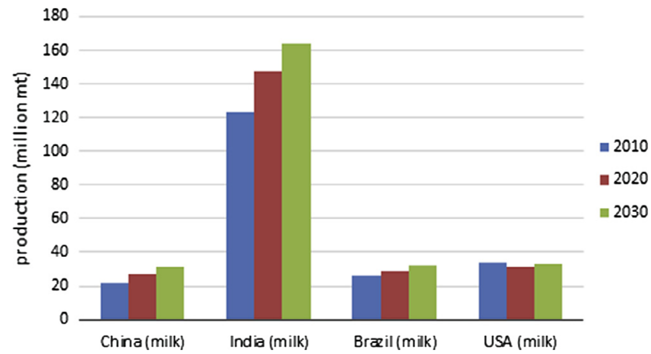


Fig. 3. Milk production for key countries. *Source:* IMPACT model simulations.

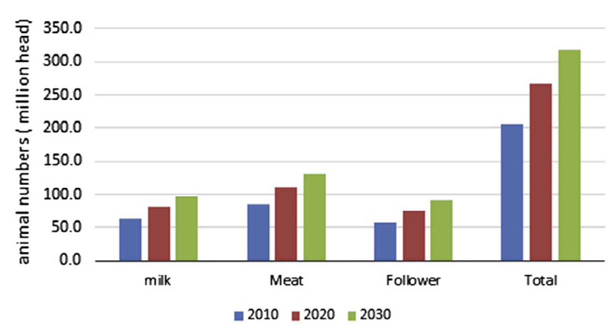


Fig. 4. Large ruminant numbers for China. *Source:* IMPACT model simulations.

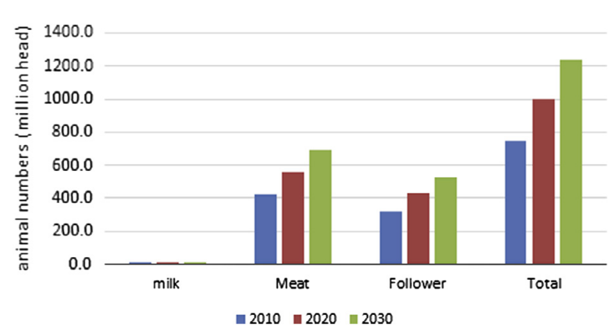


Fig. 5. Small ruminant numbers for China. *Source:* IMPACT model simulations.

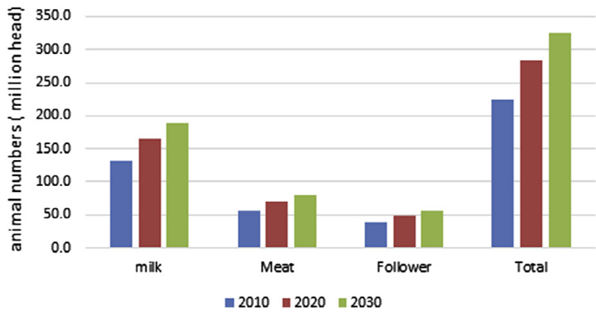


Fig. 6. Large ruminant numbers for or India. *Source:* IMPACT model simulations.

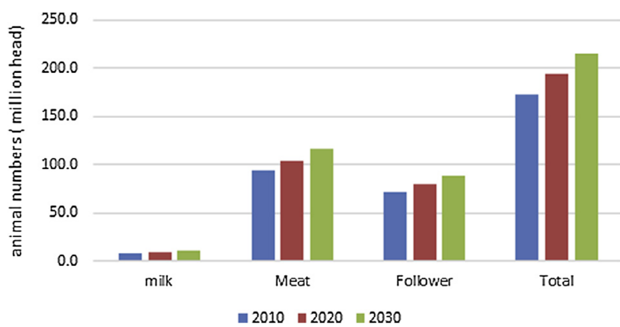


Fig. 7. Small ruminant numbers for India. *Source:* IMPACT model simulations.

By contrast to Fig. 5, the population projections of small ruminants in India (Fig. 7) shows a larger number of milk-producing animals, compared to China, and shows more dynamic growth in the number of animals slaughtered, compared to the case for large ruminants – given the special cultural status given to cattle within Indian society.

These results illustrate that the dynamics of small and large ruminant growth can vary widely between East and South Asia. Having a breakdown of functionality in the animal population projections gives us some added insight into how the different parts of the herd (i.e. the milk- versus meat-producing animals) are growing relative to each other.

Illustrative scenario – demand-side shock on livestock markets

Given the difference that the addition of livestock systems detail has brought to the explanatory power of the IMPACT model – we might also want to see if it has significantly changed the overall nature of the projections. Now we will subject the model to a demand-side shock that will illustrate how the supply-side of the model is able to adjust – and how it does so differently from the previous specification of livestock supply within IMPACT.

We will implement a scenario in which the demand for beef in China increases strongly from 2015 until the end of the projection period (2030), as is shown in Fig. 8, below.

This represents a sizable increase in the amount of beef consumed in China, over the 2nd half of the projection period, and was used as a way of seeing how differently the new supply-side of the livestock sector in IMPACT responds, compared to the earlier formulation.

Table 5, below, shows the impact of this scenario on the number of beef cattle across different regions of the world – both under the previous representation of livestock in IMPACT, as well as under the newer one.

In this, we see that there is expected expansion of the beef herd in China under the scenario, compared to the baseline – and that it is less pronounced within the new formulation of the supply-side, compared to the old one. We also see that there is a weaker supply-side expansion in other regions of the world, given that China becomes a large net importer of beef from other regions, those regions with high production and export potential, such as the Americas. Even though the new formulation of the model has reduced some of the 'instantaneous' numbers response that was possible in the older version of IMPACT – there is still an overall increase in the responsiveness of the model to the consumption shock.

If we look at how the prices within the model respond to this shock, we see that there is also a strong price response for both animal products, as well as for the key feed products (see Table 6).

The increase in the world price for beef is the strongest, across the various commodities, and especially so for the newer version of the model. Under the new formulation of the supply-side, the price increase over the baseline case is double that which is seen under the previous version of the model. This corresponds with the stronger supply response in beef response that was seen in Table 5 – and

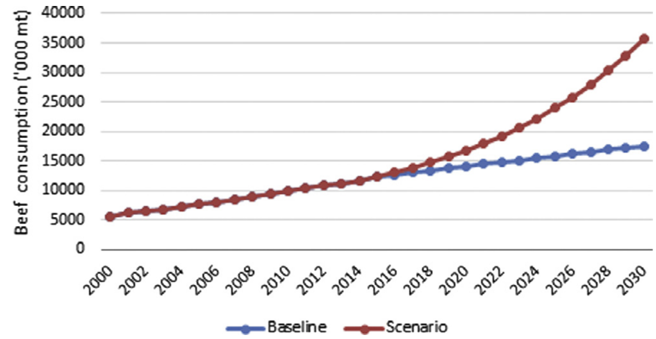


Fig. 8. Total beef consumption in China under baseline and scenario. *Source:* IMPACT model simulations.

Table 5
Comparison of numbers response for beef cattle under consumption shock – from 'old' and 'new' livestock model formulations. *Source:* IMPACT model simulations.

Region	Baseline ('000 head)		% diff in 2030 from baseline under scenario	
	2000	2030	Prev model (%)	New model (%)
N America	47,704	65,333	6.3	2.8
China	39,587	96,932	4.4	1.8
Latin America & C	58,604	104,014	7.3	3.4
SE Asia	6220	10,215	3.7	1.6
Other E Asia & P	15,758	18,997	5.8	2.5
SS Africa	24,139	40,122	4.7	2.0
Europe	60,373	67,649	4.4	1.7
S Asia	35,760	43,292	3.5	1.7

Table 6
Comparison of world price response under consumption shock – from 'old' and 'new' livestock model formulations. *Source:* IMPACT model simulations.

Region	Change in 2030 world prices from baseline	
	Prev model (%)	New model (%)
Beef	18.7	9.1
Poultry	2.6	2.6
Lamb	6.5	1.3
Pork	4.0	3.4
Eggs	2.4	2.4
Milk	0.3	−7.4
Grains	1.0	1.1
Soybean meal	2.8	3.0
Temp Oilseed meal	0.6	0.8

Table 7
Comparison of feed demand under consumption shock – from 'old' and 'new' livestock model formulations. *Source:* IMPACT model simulations.

Region	% Change in feed demand in 2030 relative to baseline		
	Demand for marketed feeds 2030 (old model)) (%)	Demand for marketed feeds 2030 (new model) (%)	Demand for Grassland biomass 2030 (%)
N America	0.4	0.4	6
China	−0.3	0.3	8
Latin America & C	0.7	0.4	3
SE Asia	0.5	0.6	4
Other E Asia & P	0.5	−0.3	5
SS Africa	0.9	0.7	2
Europe	0.7	0.2	5
S Asia	−0.2	0.9	4

reflects the fact that the supply side is "stiffer" than before, and requires a large price increase in order to get the level of supply response that is needed to meet the higher demand. This supply increase happens in terms of both the additional slaughter of animals, which is embedded in the slaughter response function (Eqs. (A9), (A10) in Appendix B) that is solved as part of the overall market equilibrium, as well as the additional growth of the beef herd that happens outside of the equilibrium solution, in-between the successive years of the model projections. Taking the overall change in beef supply (2.3% for the new model and 5.3% for the older model) and dividing it by the% change in world price for beef, we see that the implicit 'elasticity' of beef response is lower in the newer formulation of the model (0.25), compared to the implicit elasticity that can be calculated for the older model version (0.28).

If we now consider the impact that this scenario has on the feed demand within the model, we also see that the additional components that have been added convey extra information about the resource 'stress' that such a scenario implies for the livestock systems that are adjusting to it.

Table 7, below, shows the changes in the feed quantities that come from the new and old livestock components of IMPACT – both the marketed coarse grains and meals, as well as the demand for grassland from more extensive livestock production systems.

From this table we see that most of the effect of increasing herd sizes is being felt in the demand for grassland biomass, across all regions. The change is the highest in China, where the demand shock occurs – whereas the demand for marketed feeds shows a very small effect. This table illustrates the information that we would be missing if we were to only rely upon the indicator of additional feed demand and resource 'stress' coming from marketed feeds. We would have not been able to point to the additional pressure on land that is implicit in this effect, if we were only considering the cropland used for producing grain or oilseed crops that go into the making meal and oil.

Based on these results, we see that the modification of both the animal numbers response as well as the feed relationships, disaggregated across the various livestock production systems, has given us significantly different results when we simulate a demand-side shock on the system. Given the fact that the additional non-marketed feeds that we now account for play a much bigger role in the model simulations, we can also see how a supply-side shock (perhaps coming from the impacts of climate change on grassland availability) could also lead to qualitatively different implications if they were simulated in the newer formulation of the livestock sector that IMPACT now uses. This seems to justify the additional effort that was spent in differentiating the livestock systems and spending time to distinguish the underlying feed relationships that underpin them – and provides strong encouragement for continuing along this line of research to further improve and elaborate upon a more detailed and disaggregated representation of livestock production systems.

Implications

Based on these results, we can draw a number of conclusions and implications for the work that has been done to extend and improve the representation of livestock within a multi-market equilibrium model, like IMPACT.

Firstly, the disaggregation of production systems characteristics is a necessary step to understanding the underlying dynamics of the supply-side of markets. Just in the same way that rainfed crops experience very different stresses and constraints to growth, compared to irrigated crops – we would expect that the various livestock production systems also face very different barriers to growth. Even though the underlying biology of a bovine or small ruminant might be similar – the differences in feeding regimes would be expected to have a very strong impact on how the different systems might react to similar market-driven price changes and policy shocks. In order for policy makers and analysts to understand where the possibilities for response, growth and recovery from shocks might lie – they must understand the underlying production characteristics of the relevant systems.

Secondly, the differences between regions can be more clearly draw out if one also has a perspective on the underlying production characteristics that might distinguish them. Given the strong, expected future demand for livestock products – analysts will be in a better position to anticipate where the supply responses will take place in order to meet those demands, if they have a good understanding of these regional differences.

Lastly, in order to be able to appreciate how environmental shocks such as climate change will be most keenly felt – one must evaluate the supply response of livestock, as a function of feed availability, across the various systems. Where there is greater reliance on grasslands and crop residues, the impacts of changes in rainfalls might be more pronounced on the availability of feed (and the production performance of the animals), compared to those systems that can adjust more easily through market-sourced feed concentrates. As the environmental stress increases in some regions – like the dryland regions of Sahelian and Soudanian Africa – the most effective mechanisms for adjustment might be in changing sources of feed (and, essentially, shifting the nature of the production systems themselves). There is still much work to be done on understanding the impacts of climate change on livestock – and adopting a systems-focused perspective on livestock policy analysis will greatly facilitate this task for researchers, in the future.

While other expansions could be made to the model to account for differences on the consumption side – such as the difference between urban and rural consumption of animal products – we feel that a major step forward has been taken in expanding the supply side of the model, to capture production heterogeneity. The complexities of livestock systems cannot be fully captured in a macro-level, multi-market model such as this – especially if it touches upon the joint production and consumption decisions that characterize the behavior of pastoralists in poorer countries. Those are best handled in a model that can make better use of micro-data than a global model like IMPACT, and might use the market prices generated by IMPACT as an exogenous external force that drives their micro-level behavior. With an improved supply-side, trying to make such a linkage might be more feasible and meaningful than it would have otherwise been, with the older specification of livestock in IMPACT. Therefore the improvements described in this paper provide a good basis for moving forward on such a research agenda.

Appendix A: Base equations for animal numbers, production and livestock feed demand in IMPACT

Animal numbers, unit production and total volume of livestock commodity are captured in Eqs. (A1)–(A3) following. Livestock feed demand is calculated in the baseline model as in Eq. (A4).

$$AL_{tni} = \alpha_{tni} \times (PS_{tni})^{\varepsilon_{iin}} \times \prod_{j \neq i} (PS_{tnj})^{\varepsilon_{ijn}} \times \prod_{b \neq i} (PI_{tnb})^{\gamma_{ibn}} \times (1 + gSL_{tni}); \tag{A1}$$

$$YL_{tni} = (1 + gYL_{tni}) \times YL_{t-1,ni}; \tag{A2}$$

$$QS_{tni} = AL_{tni} \times YL_{tni}; \tag{A3}$$

$$QL_{tnb} = \beta_{tnb} \times \sum_{l} (QS_{tnl} \times FR_{tnbl}) \times (PI_{tnb})^{\gamma_{bn}} \times \prod_{o \neq b} (PI_{tnb})^{\gamma_{bon}} \times (1 + FE_{tnb}); \tag{A4}$$

where
- AL = number of slaughtered livestock
- YL = livestock product yield per head
- QS = quantity produced of livestock product
- QL = derived demand for livestock feed
- PS = producer price of output
- PI = price of intermediate (feed) inputs
- i, j = commodity indices specific for livestock
- b = commodity index specific for feed crops used as livestock feeds
- gSL = growth rate of number of slaughtered livestock
- gYL = growth rate of livestock yield
- α = intercept of number of slaughtered livestock
- ε = price elasticity of number of slaughtered livestock
- γ = feed price elasticity
- n = country index
- t = time index
- FR = feed ratio
- FE = feed efficiency improvement
- PI = the effective intermediate (feed) price
- b,o = commodity indices specific for feed crops
- γ = price elasticity of feed demand
- β = feed demand intercept

It is important to note from the equations is that the numbers of animals slaughtered (Appendix A, Eq. (A1)) is a composite function with an endogenous price-driven component and an externally-defined growth rate factor. Production per head (Eq. (A2)) on the other hand is entirely driven by a yield growth rate defined outside of the model specifications. The economic unit of production for livestock commodities as represented in the IMPACT model is the country. Livestock feed demand within this economic unit is responsive to volumes of livestock production, market prices of feed crop commodities and fixed feed conversion and efficiency improvement factors.

Appendix B: Modified equations for animal numbers, production and livestock feed demand in IMPACT

Enhancements made to the measurement of unit production of livestock commodities are represented in Eqs. (A5) and (A6). The calculation of livestock numbers (Appendix A, Eq. (A1)) was modified as in Eqs. (A7)–(A10) following. Eqs. (A11)–(A15) capture the new way in which total livestock feed demand is calculated and allocated, distinguishing marketed feed grains and concentrates from non-marketed livestock feeds.

$$YL_{fli} = Exp(\phi 1_{fli} + \sum_{d} \sigma 1_{flid} * Log(QX_{flid})); \tag{A5}$$

$$YL_{fli} = \phi 2_{fli} + \sum_{d} (\sigma 1_{flid} * QX_{flid}) + \sum_{d} \sum_{e} (\sigma 2_{flide} * QX_{flid} * QX_{flie}); \tag{A6}$$

$$NL_{t+1,nh} = (NL_{tnh} - SL^{meat}_{tnh}) \cdot (1 + gNL_{t,r \supset c,h}); \tag{A7}$$

$$NL_{tnh} = \sum_{z} NL^{z}_{tnh}; \tag{A8}$$

$$SL^{meat}_{tnh} = \delta^{meat}_{tnh} \cdot NL^{meat}_{tnh}; \tag{A9}$$

$$\delta_{tnh} = f(PS_{t,n,j \cap h}) \leq 1.0; \tag{A10}$$

$$\eta_{tnb} = \vartheta_{tnb} \cdot (PI_{tnb})^{\lambda_{bn}}; \tag{A11}$$

$$QL_{tnb} = \eta_{tnb} \cdot QLMkt_{tn}; \tag{A12}$$

$$QLMkt_{tn} = \sum_{d} \sum_{h} \sum_{l \subset f} \sum_{f \subset n} (NL^{l,fpu}_{tnh} \cdot Q\tilde{X}_{flhd}); \tag{A13}$$

$$NL^{l,fpu}_{tnh} = NL_{tnh} \cdot v1_{lfh} \cdot v2_{lfh}; \tag{A14}$$

$$Q\tilde{X}_{flhd} = QX_{flhd} \cdot conv_{fl} \tag{A15}$$

where
- NL = total number of livestock animals in heads
- CL = number of slaughtered animals
- YL = livestock product yield per head
- QL = livestock feed demand (of crop b)
- $QLMkt$ = total demand of marketed feeds
- $Q\tilde{X}$ = feed intake per animal unit in MT/year
- QX =feed intake per tropical livestock unit (TLU) in MT/year
- gNL = growth rate of animal numbers
- δ = share of animals in meat herd that are slaughtered
- ϕ = yield intercept
- σ = coefficient on feed variable
- QX = feed intake per TLU in MT/year
- d,e = indices of feed categories
- η = share of total marketed feeds allocated to feed crop b
- ϑ = intercept of feed demand
- PI = the effective intermediate (feed) price
- γ = price elasticity of feed demand
- v = share of animals in (1) food production unit (2) livestock production system
- $Conv$ = factor converting tropical livestock units (tlus) to animal head units
- f = food production unit
- l = livestock production system
- t = time
- r = region
- n = country
- b = index of (feed crop) commodities (corn, soybean, etc)
- i, j = index of (livestock) commodities (beef, lamb, milk, poultry, pork, eggs)
- h = index of ruminant type by species (cattle; sheep and goat)
- z = index of ruminant type by function (meat, milk, followers)

d = index of feed categories (grains, residues, pastures, occasional feeds)
conve = factor converting tropical livestock units (tlus) to animal head units

Appendix C: Global Livestock Systems for enhanced IMPACT model

No.	Sere & Steinfeld/FAO designation	Description	IMPACT model designation
1.	LGY	Rangeland Based – Hyper Arid	LGA
2.	LGA	Rangeland Based – Arid/Semi-Arid	LGA
3.	LGH	Rangeland Based – Humid/Sub-Humid	LGH
4.	LGT	Rangeland Based – Temperate/Tropical Highland	LGT
5.	MRY	Mixed Rainfed – Hyper Arid	MRA
6.	MRA	Mixed Rainfed – Arid/Semi-Arid	MRA
7.	MRH	Mixed Rainfed – Humid/Sub-Humid	MRH
8.	MRT	Mixed Rainfed – Temperate/Tropical Highland	MRT
9.	MIY	Mixed Irrigated – Hyper Arid	MRA
10.	MIA	Mixed Irrigated - Arid/Semi-Arid	MRA
11.	MIH	Mixed Irrigated - Humid/Sub-Humid	MRH
12.	MIT	Mixed Irrigated - Temperate/Tropical Highland	MRT
13.	Urban	Landless production in Urban Areas	Urban
14.	Other	All other categories	Other

Quantification of the livestock systems followed Herrero et al. (2013). According to the data available from that work, animal stocks in mixed livestock systems accounted for the largest share of global populations of ruminant animal populations. More than 60 percent of cattle populations in developing countries are to be found in the mixed crop-livestock systems, while grassland based and undefined systems (which would include more of smallholder systems in urban and peri-urban areas) together account for 35 percent of cattle populations, and landless intensive cattle operations in urban/peri-urban systems are only 5 percent of cattle numbers in developing countries. In comparison, cattle distributions may be more evenly spread across systems in developed countries. Small ruminant livestock distributions basically follow the same patterns as cattle distributions globally. It might be important to note, however, that sheep and goat may be found in greater numbers on rangelands (than in mixed systems) in developed countries. The distributions of livestock populations by regions and systems can have implications for designing appropriate instruments for livestock sector development. As such, projections of region-system distributions of livestock production are to be tracked from runs of IMPACT model version(s) that feature livestock production systems disaggregation.

Appendix D: Feeding regimes: Possible combinations of feed rations for global livestock production systems

No.	Ration type	Percentage of all FPU–LPS using regime	
	Single Feed	27.55	
1.	Grains only[*]		
2.	Pastures only		26.77
3.	Crop residues/Stovers only[a]		
4.	Occasional feeds only		0.68
	Two-Feed	53.28	
5.	Grains and Pastures		34.98
6.	Grains and Crop Residues[a]		
7.	Grains and Occasional feeds		5.11
8.	Pastures and Residues		2.60
9.	Pastures and Occasional Feeds		10.59
10.	Crop Residues and Occasional Feeds[a]		
	Three-Feed	17.10	
11.	Grains, Pastures and Crop Residues		10.10
12.	Grains, Pastures and Occasional Feeds		4.17
13.	Grains, Crop Residues and Occasional Feeds		0.23
14.	Pastures, Crop Residues and Occasional Feeds		2.60
	Four-Feed	2.06	
15.	Grains, Pastures, Crop Residues and Occasional Feeds		2.06
–	All	100	

[a] Combinations not observed in the data.

Global systems-disaggregated data on animal production was obtained from recent work concluded at ILRI and IIASA (Herrero et al., 2013). This data set contains estimates of year 2000 stocks of cattle, sheep and goats, poultry and pigs; annual production of beef, lamb, poultry and chicken meat, milk and eggs) per tropical livestock unit (TLU) of animal in metric tonnes; and annual feed requirements per TLU of livestock animals in production and follower herds. Information on livestock diets is available for four categories of feed types – grains & concentrates,[6] crop residues, pastures, and *other* feeds. Grains & concentrates' data is further detailed for grains (corn, rice, sorghum, millet and other cereals), pulses (total), legumes (soya only), oilseeds (total), and other crops (residual) categories corresponding to commodity classifications used for the FAO national statistics databases. Using spatial mapping technique, the data values were appropriately associated to the food production unit-based livestock production systems (i.e., FPU–LPS) developed for IMPACT.

Of 15 possible combinations of the four major feed categories, 12 were observable in the data on diets required/fed to support livestock production globally. Also observed from the data, and as may be expected for livestock production with multi-species or products, are different feed combination types or *feeding regimes* being adopted within the same FPU-LPS. This variability refers to differences in the feed types used in combination and not simply to amounts of the same feed being utilized. For example, beef cattle in the Rangeland – Temperate/Tropical Highland system of

[6] 'Grains and concentrates' data included details on grain (corn, rice, sorghum, millet and 'other cereals'), pulses (total), legumes (soya only), oilseeds and 'other crops' categories correspondent to commodity classifications of the FAO.

Amazon Brazil employed a pastures-only feeding program for beef cattle and a pastures & grains regime for dairy. For model tractability purposes, we assumed that the feeding regimes observed in the base year are representative of the FPU-LPS 'preferred feeding' for the specific livestock animals (e.g., dairy herds, beef herds).

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