Development and evaluation of an integrated simulation model for assessing smallholder crop–livestock production in Yucatán, Mexico

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Mixed farming systems constitute a large proportion of agricultural production in the tropics, and provide multiple benefits for the world's poor. However, our understanding of the functioning of these systems is limited. Modeling offers the best approach to quantify outcomes from many interacting causal variables in these systems. The objective of this study was to develop an integrated crop–livestock model to assess biophysical and economic consequences of farming practices exhibited in sheep systems of Yucatán state, Mexico. A Vensim™ dynamic stock-flow feedback model was developed to integrate scientific and practical knowledge of management, flock dynamics, sheep production, partitioning of nutrients, labor, and economic components. The model accesses sheep production and manure quantity and quality data generated using the Small Ruminant Nutrition System (SRNS), and interfaces on a daily basis with an Agricultural Production Systems Simulator (APSIM) model that simulates weather, crop, and soil dynamics. Model evaluation indicated that the integrated model adequately represents the complex interactions that occur between farmers, crops, and livestock.

1. Introduction

Seré and Steinfeld (1996) defined mixed farming systems as those in which more than 10% of the dry matter fed to livestock comes from crop by-products or stubble, and more than 10% of the value of production comes from non-livestock farming activities. More simply, they are enterprises where animal husbandry and crop cultivation are integrated components of one farming system. Mixed farming systems are extremely important in developing countries, where they supply most of the meat (50%) and milk (90%) (Thornton and Herrero, 2001). About two thirds of the world's rural poor rely on mixed crop–livestock systems for their livelihoods (ILRI, 2000).

In mixed farming systems, crop and livestock activities compete for the same scarce resources including land, labor, capital and skills. Consequently, in general the productivity of livestock in mixed systems (such as milk production per animal per day, growth and reproduction rates), is lower than in specialized systems (LEAD, 2007). This has sometimes led to the interpretation that mixed systems are less productive; however, although there may be lower productivity per unit land or animal in one enterprise, higher productivity overall is common (McIntire et al., 1992).

Livestock play many vital roles in the households and economies of the developing world, including producing food and power, generating income, storing capital reserves, and enhancing social status (Randolph et al., 2007). In addition, livestock can be used for weed control, production of manure for fertilizer and fuel, and production of fiber (ILRI, 2000).

Crop–livestock integration is generally driven by increased population pressure (McIntire et al., 1992), which is often the principal avenue for farmers to intensify their farming systems. Crop–livestock integration may also allow diversification of production and better distribution of labor throughout the year, as well as distribution of tasks among different components of the household (Ghirotti, 2004). Livestock can affect the cycling of nutrients, opening alternative pathways, such as importation of nutrients from common land, and affecting the speed and efficiency at which nutrients can be converted to plant-useable forms (Delve et al., 2001). Inclusion of livestock in mixed farming systems can provide an alternative use for crop residues. For example, if farmers need to plant a crop soon after harvesting a previous one, stubble incorporation may not be feasible, and farmers may resort to burning, resulting in increasing carbon dioxide emissions (Blackburn, 2004). In contrast, livestock in mixed farming systems can be used to remove and process stubble, potentially reducing the losses of carbon and nutrients. Blending crops and livestock has the potential to maintain ecosystem function and health and help prevent agricultural systems from becoming too 'brittle', by promoting greater biodiversity and an increased capacity to absorb shocks to the natural resource base (Holling, 1995).

The interactions between livestock, crops and natural resources in mixed farming systems are many and complex. This complexity has meant that their worth has not been well quantified or appreciated, leading to limited ability to determine the optimum system under specific conditions. Disentangling interactions between crops and livestock is difficult, and consequently studies have not always reflected the entire value of system components. If livestock are to play a sustained role in improving the livelihoods of the many millions of people who currently depend on them, improved understanding is needed about how these systems function, and tools are needed for improving system performance for each unique circumstance. Thornton and Herrero (2001) argued that because of the many subtle yet significant interactions that occur, modeling offers the only feasible way of assessing the potential impacts of intervention and changes to these production systems.

We chose Yucatán State, Mexico, as a target region on which to base model development and evaluation. The traditional cropping practice of the region is a form of shifting cultivation, known locally as *milpa*, where two to three years of cultivation are followed by a 10- to 20-year period of forest fallow (Kessler, 1990). Although livestock ownership has long been a part of traditional agriculture (Steggerda, 1941), production of hair sheep is a more recent practice that is becoming increasingly common due to strong demand for lamb and mutton in Mexico City (Parsons et al., 2006). For smallholder farmers sheep present a development opportunity, with potential to diversify income and access potential complementarities between cropping and livestock, such as manure production, alternative pathways of nutrient cycling, and opportunity to use crop products for animal production.

Many previous modeling efforts have included the crop, livestock and soils components relevant for assessment of integration or intensification of mixed farming systems (e.g., Gradiz et al., 2007; Herrero et al., 2007; Castelan-Ortega et al., 2003); AusFarm; van Ittersum et al., 2008). These models represent a range of systems from the very specific, such as Gradiz et al. (2007) that focuses on a beef-sugarcane system in Japan, to generic modeling systems such as IMPACT (Herrero et al., 2007). IMPACT is a useful generalized tool to characterize diverse crop–livestock systems, but lacks the ability to dynamically simulate scenarios based on these systems. Many other models simulate a range of crops and systems but development and evaluation has been for a particular geographic region, such as the SEAMLESS framework for the European Union (van Ittersum et al., 2008). Another location-specific example is AusFarm (Moore, 2001) which is a highly flexible whole-farm model developed for Australian farming systems. AusFarm is based on the GRAZPLAN pasture and animal management models (Donnelly et al., 2002), but can also utilize a limited range of APSIM crop and soil models (Keating et al., 2003) through the common modeling protocol (Moore et al., 2007). An example of a modeling framework developed specifically for the developing world is the NUANCES-FARMSIM model (Van Wijk et al., 2009), which is focused on smallholder systems of Sub-Saharan Africa. The integration of crop and soil (Tittonell et al., 2007, 2008), livestock (Rufino et al., 2007a), manure (Rufino et al., 2007b), and labor models (Van Wijk et al., 2009, Supplementary material) in the form of NUANCES-FARMSIM (Van Wijk et al., 2009) has only recently entered the literature, and further assessment will be useful to enhance confidence in its ability to represent a wide range of systems and research questions.

Despite the numerous extant modeling frameworks useful to assess crop–livestock integration, continued development of alternative frameworks capable of addressing both general and location-specific characteristics and issues is advisable given the diversity of agricultural systems in which crop and livestock components interact. In light of this, the key contribution to the modeling literature of our work is the integration of well-developed livestock nutrition and crop simulation models within a dynamic stock-flow-feedback structure for shifting cultivation systems with maize and sheep as key components. To date, this framework has been applied empirically for a single location in tropical Mexico.

The principal objective of this simulation model was to assess the biophysical and economic consequences of selected suites of management decisions and farming practices observed in the smallholder *milpa*-sheep system of Yucatán State. A connected aim was to represent combinations of practices, but not simulate and predict the circumstances that lead farmers to choose these practices. In other words, the research question could be phrased as: 'Given a farmer-selected set of management decisions representing different levels of crop–livestock integration, what are the potential biophysical, labor and, economic outcomes?' This paper describes the development of the model and provides a general discussion of its behavior and limitations. A companion paper describes performance of the model when applied to specific scenarios, and discussion of the biophysical and economic implications of the results.

2. Description of the integrated model

The model is an integrated crop–livestock model, with dynamic linkages among crop, livestock, and socioeconomic components. It represents an individual farm household in Yucatán, Mexico with access to common land for (maize) cropping and grazing. This household may also own a small number of sheep. The model is deterministic, simulating biological and economic outcomes without optimizing behavior by the household. The time unit for simulation of the model is one day, and the time horizon for simulation is ten years. The model can simulate a range of management options consistent with observed management practices. These practices include, flock size, source and quality of feeds, grazing or cut and carry of cultivated grass, maize cultivation, grazing or cut and carry of maize stover, feeding of on-farm produced maize grain, use of manure on maize or cultivated grass, frequency of manure use, and fertilizer use.

The main strength of this modeling approach is its integration of two existing models, the Small Ruminant Nutrition System (SRNS) and the Agricultural Production Systems Simulator (APSIM). The latter is a well-developed crop model that adequately represents a wide variety of crops in developing countries (Stephens and Middleton, 2002). Similarly, the SNRS is based on the Cornell Net Carbohydrate and Protein System (CNCPS), which is widely regarded as a skilled model for estimating ruminant performance for a wide range of feed sources. These models are linked with the socioeconomic component of the integrated model using the stock-flow feedback structure of system dynamics modeling (Sterman, 2000). More specific comparisons with other modeling systems are discussed in the description of the model components below.

2.1. Components of the integrated model

The Agricultural Production Systems Simulator (APSIM) (Keating et al., 2003) simulates biophysical processes in farming systems, particularly focusing on combining accurate yield estimation with prediction of long-term consequences of farming practices on soil resources. A feature of APSIM is its modular modeling framework (Jones et al., 2001) where users construct a model by selecting a logical combination of modules from a suite of crop, soil, and utility modules. The APSIM module Venlink (Smith et al., 2005) links APSIM with Vensim™ (Ventana Systems Inc), an icon-based dynamic modeling software package. Vensim™ has the advantage of ease of use, allowing users with limited code-based programming skills to design, build, and maintain their own models (Smith et al., 2005). The Venlink module enables users to combine their own Vensim™ models with the existing APSIM framework, communicating by input and output variables (Smith et al., 2005).

To simulate sheep nutrition we used the Small Ruminant Nutrition System (SRNS) (http://nutritionmodels.tamu.edu/srns.htm). It is based on the Cornell Net Carbohydrate and Protein System for sheep (CNCPS-S) (Cannas et al., 2004) which predicts energy and protein requirements and availability in sheep, using a mechanistic rumen model.

2.2. Overview of the integrated model

Although there are numerous possible species of crops and forages that could be modeled, the model structure represents maize without companion crops, but with competition from weeds to enable realistic simulation of yields. Secondly, the model structure includes Guinea grass (*Panicum maximum* L.) as the chosen forage species, a reasonable simplification given its widespread presence in Yucatán (Parsons et al., 2006). The components of the system modeled and the inter-relations between them are shown in Fig. 1. Three APSIM 'paddocks' (*milpa*, Guinea grass, and corral) are simulated simultaneously, using a calculation interval of one day, necessary to capture the response of crops to environmental conditions. This differs from existing integrated models such as Shepherd and Soule (1998), which used a time unit of one year. The Vensim™ model component includes management, flock dynamics, sheep production, partitioning of nutrients, labor, and economic outcomes. Data outputs from SRNS simulations are used as inputs to the Vensim™ model. APSIM and Vensim™ are linked through the Venlink module by specific interface variables (Table 1). The daily communication between APSIM and Vensim™ enables dynamic system feedback. For example, application of manure to cultivated forage can rapidly affect the quantity and quality of forage produced, which can in turn affect livestock production and the quantity and quality of manure, thus closing the feedback loop. Such dynamic feedback contrasts with models such as Castelan-Ortega et al. (2003) wherein static crop model outputs are used as inputs for the integrated model. Like our integrated model, the NUANCES-FARMSIM model (van Wijk et al., 2009) includes dynamic feedback between components, but does not, however, include an economic module.

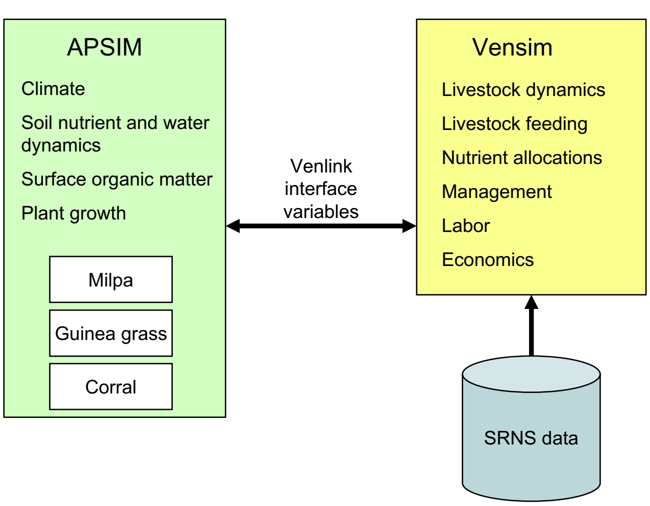

Fig. 1. The components, inter-relations between components, and disciplinary sections of the integrated model.

2.3. APSIM components of the integrated model

McCown et al. (1996) described the detailed workings of APSIM. Parsons (2008) details the climate data used and methods for soil parameterization used in this study. The following discussion describes using APSIM to simulate *milpa*, forage, and manure and feed refusal dynamics.

2.3.1. Milpa simulation in APSIM

The integrated model simulates *milpa* production using the APSIM Maize module in combination with the Weed module (to specify the weed) and the Canopy module (to enable inter-plant competition). The APSIM component of the model contains manager statements (Table 2) constructed to simulate the *milpa* and the necessary linkages with other model components. Maize (Supplementary material, Table 1) and soil characteristics (Supplementary material, Table 2) were parameterized in APSIM to represent typical Yucatán conditions. Additional APSIM constants are detailed in Supplementary material Table 3.

When the integrated model run is initiated the following events occur. For first year maize crops, the soil nitrogen, and soil and surface organic matter are reset to levels that represent freshly cleared forest. The second year crop is sown into the same soil as the first year crop, with increased competition from weeds, and at the end of the second year the soil characteristics are reset to represent land after fallow. Maize and weeds are sown within specified sowing windows and in response to a specified moisture threshold. Weeding occurs at a threshold weed biomass, or at a maximum time after emergence, simulating farmer efforts to reduce weed competition. Urea may be added to the *milpa* through urine or fertilizer addition. Manure and feed refusals may also be added to the *milpa* at rates and C:N ratios specified by Vensim™. Maize is harvested at maturity, and the grain yield and nitrogen concentration are monitored in Vensim™. The fraction of maize stover removed at harvest is specified in Vensim™, which tracks biomass and nitrogen concentration; the remaining stover portion becomes part of the surface organic matter for the paddock.

2.3.2. Guinea grass simulation in APSIM

The model simulates Guinea grass growth using the APSIM Bambatsi module (*Panicum coloratum* var. *makarikariense*) with modifications to the configuration settings for target nitrogen concentrations for leaf (0.017 kg kg^{-1}) and stem (0.012 kg kg^{-1}) (based on Bamikole et al., 2004; Brâncio et al., 2003; Evitayani et al., 2005; Perissato-Cano et al., 2004). The model contains APSIM manager statements (Table 2) constructed to simulate Guinea grass production with necessary linkages with other model components. Values of key APSIM constants are contained in the Supplementary material. Operations include sowing, adding manure, fertilizer, and feed refusals, cutting or grazing, and harvesting.

2.3.3. Corral manure and feed refusal simulation in APSIM

The model simulates manure, feed refusal, and stover dynamics in the *milpa* and Guinea grass paddocks and the corral using the

Table 1
Vensim variables that interface with APSIM in the integrated crop–livestock model.

Vensim name	Units	Description
Maize		
APSIM to Vensim		
Maize grain harvested per ha	kg DM ha^{-1} day^{-1}	The rate of maize grain harvested per hectare in APSIM
Maize grain percent N	kg N kg DM^{-1}	The N concentration of maize grain harvested in APSIM
Maize stover harvested per ha	kg DM ha^{-1} day^{-1}	The quantity of maize stover harvested per hectare in APSIM
Maize stover percent N	kg N kg DM^{-1}	The N concentration of maize stover harvested in APSIM
Vensim to APSIM		
Adjusted manure to milpa	kg manure ha^{-1} day^{-1}	The rate of manure addition to the milpa
Adjusted refusals to milpa	kg DM ha^{-1} day^{-1}	The rate of refused feed addition to the milpa
Manure C:N to milpa	kg C kg N^{-1}	The carbon to nitrogen ratio of manure added to the milpa
Milpa cultivation cycle	year	The current cultivation cycle of the milpa.
Refusal C:N to milpa	kg C kg N^{-1}	The carbon to nitrogen ratio of refused feed added to the milpa
Stover fraction harvested	dmnl	The fraction of maize stover that is harvested
Urea to milpa	kg N ha^{-1} day^{-1}	The rate of urea application per hectare to the milpa from fertilizer and livestock
Guinea grass		
APSIM to Vensim		
Grass leaf N per ha	kg N ha^{-1}	The N concentration of standing grass leaf in APSIM
Grass leaf per ha	kg DM ha^{-1}	The quantity of standing grass leaf per hectare in APSIM
Grass stem N per ha	kg N ha^{-1}	The N concentration of standing grass stem in APSIM
Grass stem per ha	kg DM ha^{-1}	The quantity of standing grass stem per hectare in APSIM
Vensim to APSIM		
Adjusted manure to grass	kg manure ha^{-1} day^{-1}	The rate of manure addition to grass
Adjusted refusals to grass	kg DM ha^{-1} day^{-1}	The rate of refused feed addition to grass
Grass harvested per ha	kg DM ha^{-1} day^{-1}	The rate of grass per hectare to be harvested in APSIM
Manure C:N to grass	kg C kg N^{-1}	The carbon to nitrogen ratio of manure added to grass
Refusal C:N to grass	kg C kg N^{-1}	The carbon to nitrogen ratio of refused feed added to grass
Urea to grass	kg N ha^{-1} day^{-1}	The rate of urea application per hectare to grass from fertilizer and livestock
Corral		
APSIM to Vensim		
Manure C in pile	kg C ha^{-1}	The quantity of carbon in manure per hectare in the corral
Manure in pile	kg manure ha^{-1}	The quantity of manure per hectare in the corral
Manure N in pile	kg N ha^{-1}	The quantity of nitrogen in manure per hectare in the corral
Refused feed C in pile	kg C ha^{-1}	The quantity of carbon in refused feed per hectare in the corral
Refused feed in pile	kg DM ha^{-1}	The quantity of refused feed per hectare in the corral
Refused feed N in pile	kg N ha^{-1}	The quantity of nitrogen in refused feed per hectare in the corral
Vensim to APSIM		
Adjusted manure to corral	kg manure ha^{-1} day^{-1}	The rate of manure addition to the corral
Adjusted refusals to grass	kg DM ha^{-1} day^{-1}	The rate of refused feed addition to the corral
Empty manure pile	dmnl	A signal sent to APSIM that the manure and refused feed pile should be emptied
Manure C:N to corral	kg C kg N^{-1}	The carbon to nitrogen ratio of manure added to the corral
Refusal C:N to grass	kg C kg N^{-1}	The carbon to nitrogen ratio of refused feed added to the corral

APSIM SurfaceOm module. Decomposition of surface organic matter in the module depends on moisture, temperature, C:N ratio, and soil contact, and results in carbon loss as CO_2, and transfer of carbon and nitrogen to the soil (Probert et al., 1998). For the corral, the model assumes that the manure and feed refusal organic matter is uncovered and exposed to rain. Manure and feed refusal biomass, carbon, and nitrogen levels are sent to Vensim™. Manure and feed refusals are added to the corral at rates and C:N ratios specified by Vensim™. Depending on management options, a signal is sent from Vensim™ and the corral is emptied of manure and feed refusals and allocated to the grass or *milpa*.

2.4. The Vensim™ model

The following discussion describes the model structure (variables and equations) and constants and baseline parameter values. Equations are listed in Supplementary material Table 3, and are referred to in the text by their number. Constants and equation parameters are listed in the Supplementary material. The companion paper lists the values of parameters used for scenario simulations. Constants and parameter values were decided upon through reference to the literature, interviews with producers (Parsons et al., 2006), observations made of producer practices, and discussion with a panel of scientists with disciplinary expertise or local knowledge of these systems.

2.5. Livestock dynamics

Sheep are modeled in age-weight groups rather than as discrete animals. Sheep groups are categorized according to their lower and upper weights (Supplementary material, Table 5). Animals move through different groups as they increase in weight (Fig. 2). For example, female lambs are born at an assumed constant weight and progress to young females when a weaning weight is achieved. Young females grow until the weight required to be retained as a growing ewe is achieved, at which time sheep are either retained as growing ewes if needed as replacements, or they become female finishing sheep. Female finishing sheep are sold when a target sale weight is reached. Growing ewes become mature ewes at a specified weight, and mature ewes are retired from the flock after a specified number of parturitions. Male sheep follow an analogous development path.

Values for constants, and ranges for parameters used in the following description of the livestock dynamics sub-section are contained in the Supplementary material (Table 6). The lamb birth rate (Eq. (1)) is calculated separately for mature and growing ewes,

Table 2
Description of APSIM manager modules used to develop the integrated crop–livestock model.

Name	Description
Maize	
Add dung to milpa	Adds dung to milpa at signal from Vensim, with variable C:N ratio
Add refusal to milpa	Adds feed refusals to milpa at signal from Vensim, with variable C:N ratio
Add urea to maize	Adds urea nitrogen to milpa at signal from Vensim
Adjust for milpa age	Resets soil water and organic matter in a first year milpa, and sets weed density based on milpa age
Maize harvest	When maize is ripe, orders harvest of crop
Maize sowing signal	Sends signal to Vensim that maize has been sown
Record maize yield to Vensim	At harvest, sends grain biomass and nitrogen content to Vensim
Remove maize stover at harvest	At harvest, specifies (from Vensim) the fraction of maize stover removed and its nitrogen content
Sow using a variable rule with intercropping	Sows maize within a specified sowing window, and at a specified plant spacing
Sow weeds using a variable rule with intercropping	Sows weeds within a specified sowing window, at a variable density (set by 'adjust for milpa age')
Weeding at threshold biomass or maximum days	Sets number of in-crop and fallow weedings, threshold weed biomass, and maximum days after weed emergence to weeding
Guinea grass	
Add dung to grass	Adds dung to grass at signal from Vensim, with variable C:N ratio
Add refusal to grass	Adds feed refusals to grass at signal from Vensim, with variable C:N ratio
Add urea to grass	Adds urea nitrogen to grass at signal from Vensim.
Grass biomass status	Sends current grass leaf and stem biomass and nitrogen to Vensim
Grass cutting rule	At signal from Vensim cuts specified fractions of the leaf and stem biomass.
Sow grass	Sows grass on a set date
Corral	
Add dung to corral	Adds dung to corral at signal from Vensim, with variable C:N ratio
Add refusal to corral	Adds feed refusals to corral at signal from Vensim, with variable C:N ratio
Dung pile status	Sends current dung pile biomass, carbon, and nitrogen, to Vensim
Empty dung pile	At signal from Vensim uses an APSIM tillage function to remove dung
Refusal pile status	Sends current feed refusal pile biomass, carbon, and nitrogen, to Vensim

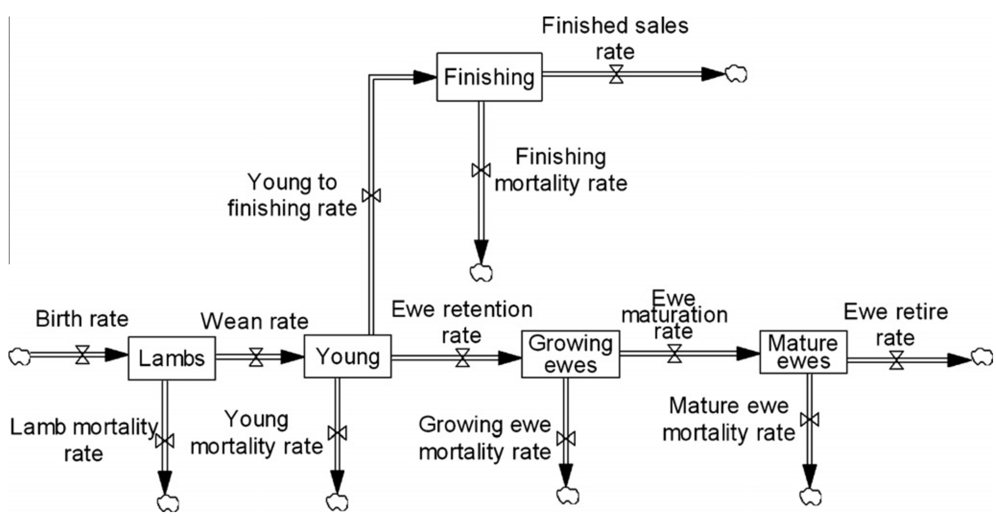

Fig. 2. The flow of female sheep through different livestock groups.

and depends on the lambing interval and the lambs born per ewe. The lambing interval (Eq. (2)) is the sum of the gestation period and the days to conception. The time delay between sheep entering and leaving a group is a function of minimum and maximum body weight and the current average daily live-weight gain (LWG). An example delay (weaning delay for lambs) is shown in Eq. (3). Similar equations are used for calculating the time delays for other sheep groups, except mature ewes and mature rams where the delay is equal to the time spent in the flock as a mature animal, and is assumed to be fixed. The Vensim™ 'Delay Material' function (Vensim™ Documentation, 2006) was used to model the outflow of sheep. With this function all sheep exit the group at the maximum weight and are partitioned into sheep that either exit to the next group or are deceased. For example, for lambs the total outflow from the stock is a pipeline delay (i.e. first in, first out) of the inflow (Eq. (4)). The total output is then partitioned into the lamb wean rate and the lamb mortality fraction (Eqs. (5)–(6)) where the lamb mortality fraction depends on the lamb wean delay and a constant fractional lamb mortality (Eq. (7)). This type of formulation is used for modeling mortality in human demographic or other animal population models (Sterman, 2000). Analogous exit and mortality calculations are used for other sheep groups.

The livestock dynamics sub-section of the model is initialized in dynamic equilibrium, meaning that all stock values are constant but flows are greater than zero. This provides more control over outcomes for the purposes of experimentation. For a given set of initial variable values, including LWGs, only the initial total numbers of ewes and rams need to be set, and all other livestock stocks and rates are calculated to initialize in dynamic equilibrium. Where the actual number of ewes or rams is different from the desired number, the model uses a goal-seeking structure to modify livestock numbers. When sheep exit the young female stock, they

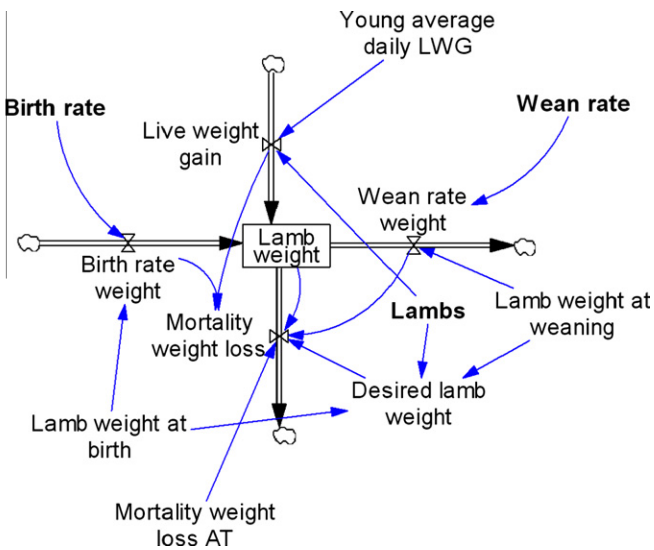

Fig. 3. Depiction of the variables and linkages used to model lamb weight as a co-flow livestock attribute. Birth rate, wean rate, and lamb numbers are depicted in bold to signify that they are auxiliary links from the livestock numbers structure. Equations and their units are shown in Table 3. Abbreviations include live-weight gain (LWG) and adjustment time (AT).

can be retained to replace ewes that die or are retired. The overall ewe loss rate is a total of the mortality and retired losses (Eq. (8)). The ewe adjustment rate (Eq. (9)) is calculated to bridge the gap between the actual and desired number of ewes, depending on the rate at which this adjustment occurs (the adjustment time). The desired ewe retention rate (Eq. (10)) is the sum of the ewe loss rate and the ewe adjustment rate, with a value of zero used if the sum is negative. The actual ewe retention rate (Eq. (11)) can only be as large as the rate of young female maturation rate, and also has a minimum value of zero. Young females exiting that are not required for ewe retention are added to the stock of females grown for finishing. An analogous set of equations is used to maintain the total rams at a desired level.

A feature of the integrated model is the co-flow structure (Sterman, 2000) which models the attributes of a stock in addition to the size of the stock. The relevant animal attribute is weight, and each sheep group stock has a correspondent co-flow stock, with units of kg of sheep. An example showing the linkages necessary for this structure for lambs (either male or female) is shown in Fig. 3. The birth rate, wean rate, and stock of lambs are depicted in bold to signify that they are auxiliary links from the livestock numbers structure previously described. The stock of lamb weight (Eq. (12)) depends on inflow from lamb births and lamb weight gain, and outflow from lambs weaned and lamb mortality. The inflow of weight due to lamb births (Eq. (13)) depends on the lamb birth rate and a specified lamb birth weight. The inflow of lamb weight gain (Eq. (14)) depends on the number of lambs and the average daily live-weight gain per lamb. The outflow of weaned lamb weight (Eq. (15)) depends on the weaning rate and a specified weaned lamb weight. The outflow due to lamb mortality (Eq. (16)) is a goal-seeking error structure designed to keep the average weight per lamb constant. It is a function of the stock of lamb weight, the other lamb weight inflows and outflows, and a desired total lamb weight (Eq. (17)) which depends on the number of lambs and an average of the birth and weaning weights.

2.6. Feeding dynamics

2.6.1. Application of SRNS for sheep production

The integrated model uses SRNS simulations for predicting sheep performance, including intake, protein and energy balance, live-weight gain, and fecal and urinary outputs. Using SRNS we developed a database of animal production using typically observed diets (Supplementary material, Table 7). SRNS simulations for ten feeding options (each composed of a feeding method and ingredients in ratios that are assumed constant for each animal group) were performed for each sheep group. Ingredients include those that are assumed to have constant quality (milk and commercial concentrate), those that vary between the wet and dry season but are not determined endogenously [Leucaena (*Leucaena leucocephala* Lam.) and native grass], and those endogenously simulated in APSIM (maize stover, maize grain, and Guinea grass). For feeding options with ingredients of variable quality it was necessary to perform multiple SRNS simulations.

The feed composition values used for the ingredients for different seasons and nitrogen limits are shown in the Supplementary material (Table 8). Values were derived from Parsons (2008), the CNCPS tropical feeds library (Tedeschi et al., 2002), and a feed composition database collated by the Universidad Autónoma de Yucatán (unpublished data). Additional input data for SRNS simulations, and other constants and parameters were based on a variety of sources in the literature described in the Supplementary material (Tables 9 and 10). For each sheep group the input data were based on an average animal at the midpoint of the body weight range. Because the physiological state of breeding animals changes, simulations were performed for monthly intervals, assuming 5 months of pregnancy followed by 3 months of lactation. For lactating ewes, an average daily milk production was used for the 3 months of lactation. Growing ewes have requirements for weight gain in addition to pregnancy or lactation; thus, ingredient ratios were specified to allow protein requirements and expected weight gains to be met.

Model outputs from SRNS include dry matter intake, live-weight gain, total fecal output, fecal crude protein, fecal fat, fecal starch, fecal fiber, fecal lignin, crude protein intake, required milk metabolizable protein, metabolizable protein for growth, and metabolizable protein for pregnancy. A number of additional calculations are required to define manure characteristics. Fecal N (Eq. (18)) is a function of fecal crude protein and a standard nitrogen fraction of crude protein. Fecal C (Eq. (19)) is the sum of multiplying fecal starch, fiber, lignin, crude protein, and fat by their corresponding carbon fractions. Urinary N (Eq. (20)) is the excess nitrogen when protein retained in growth and the conceptus and fecal and milk protein, are subtracted from the crude protein intake. The protein retained for growth (Eq. (21)) and in the conceptus (Eq. (22)) are products of the metabolizable protein required and the efficiency of metabolizable protein.

2.6.2. Guinea grass

The quantity and quality of Guinea grass (GG) leaf and stem are simulated in APSIM and recorded on a daily basis. The leaf fraction of the grass consumed (Eq. (23)) depends on the relative proportions of leaf and stem, and the fraction of grass stem refused, using a simplifying assumption that all leaf matter is consumed. The quantities of leaf (Eq. (24)) and stem (Eq. (25)) harvested depend on the total Guinea grass needed (see below) and the leaf fraction. Because some stem is refused, the quantity of stem to be harvested (Eq. (26)) is greater than the quantity consumed. The quantity of stem refused (Eq. (27)) is calculated by difference. The total desired grass to be harvested (Eq. (28)) is therefore the sum of the leaf consumed, the stem consumed, and the stem refused.

The Guinea grass actually harvested (Eq. (30)) depends on whether the desired amount is available (Eq. (31)) and the amount of Guinea grass deemed to be in excess of the needs of the farmer (Eq. (32)). The difference between the grass required for animals and the grass harvested (not including grass sold) is the amount of grass that must be purchased (Eq. (33)). The nitrogen fraction of the grass (Eq. (34)) is used to determine the quality of the grass for animal production, and depends on the N fractions of stem (Eq. (35)) and leaf (Eq. (36)).

2.6.3. Maize grain and stover

The stock of maize grain (Eq. (37)) depends on the initial quantity of grain, and the rates of grain harvested, sold, and fed to livestock. The grain harvest rate (Eq. (38)) is a product of the grain harvested per hectare (from APSIM, see Table 1) and the area of maize. Grain is sold (Eq. (39)) when there is excess stored grain (Eq. (40)) above a threshold quantity. The maximum maize grain outflow rate (Eq. (41)) depends on the minimum residence time, the time which grain must remain in storage before it exits, representing the minimum time between harvesting and sale, which prevents the stock from becoming negative. Stored grain is removed for feeding (Eq. (42)) depending on the quantity of grain required and the maximum grain outflow. Extra grain is purchased (Eq. (43)) if there is insufficient stored grain.

Concentration of nitrogen in the grain is calculated using a conserved co-flow structure, meaning no nitrogen is lost from the grain during storage. The initial quantity of grain nitrogen (Eq. (44)) is the product of the initial quantity of grain and the initial fraction of nitrogen in the grain. The stock of grain nitrogen (Eq. (45)) is controlled by the rates of grain nitrogen harvested (Eq. (46)), sold (Eq. (47)), and fed to livestock (Eq. (48)), at rates depending on the average fraction of N in the grain (Eq. (49)).

Stover is treated in an analogous manner to maize grain, with differences as follows. Whereas all maize grain fed is consumed, it is assumed that all stover leaf is consumed, but all stem is refused (assuming stover is not chopped). Thus, the total daily stover required (Eq. (50)) is a function of what is required for livestock intake, and the leaf fraction of maize stover. Stover leaf (Eq. (51)) and stem (Eq. (52)) nitrogen concentrations are used in determination of nutrients available to meet animal requirements and feed refusal quality (as detailed below).

2.6.4. Determining ingredient requirements and livestock production

To reduce the number of SRNS simulations needed, feeding options were designed so that each contained only one ingredient with nitrogen content generated by APSIM (i.e. only one of Guinea grass, maize grain, or maize stover). For these ingredients, the product consumed by livestock may be entirely produced on the farm (variable nitrogen), purchased (constant nitrogen), or a combination of the two. In circumstances where a combination is used, the N concentration of the ration is assumed to equate the N concentration of the purchased feed.

For each variable ingredient, and thus each feeding option, lower and upper nitrogen concentrations are set, as described above. The nitrogen fraction of the variable ingredient in each feeding option is defined relative to these lower and upper values, returning a value between zero and one. This variable, named ‘Feed relative N’ (Eq. (53)), is used in a number of animal production calculations, including live-weight gain, dry matter intake, fecal output, fecal N output, fecal C output, and urinary N output. These outputs are calculated for the four combinations of two seasons (dry and rainy), and two limits (lower and upper, Supplementary material Table 8), and a linear function describing the output response between the upper and lower limit. For example, total dry matter intake (Eq. (54)) is calculated for every combination of animal group, season, and feeding option.

The daily dry matter intake of ingredients involves a series of calculations with arrays of data. For each ingredient, the total dry matter intake (DMI) per sheep (Eq. (55)) is a function of the chosen feeding option DMI and the fraction of the ingredient in the feeding option. Calculations are performed for every sheep group, and the total ingredient DMI is the sum for all sheep groups. The total amount of required ingredient (Eqs. (56)–(57)) takes into account feed refusals (Eq. (58)). The feed refusal fraction in Eq. (58) is constant for most ingredients (Supplementary material, Table 10) but variable for Guinea grass and maize stover, which have variable stem refusal fractions as described above.

2.7. Manure dynamics

Manure production and use involves all sections of the integrated model. Manure output is calculated using SRNS simulations, and component outputs (fecal output, fecal N output, fecal C output, and urinary N output) are calculated in a similar way to DMI detailed above, with the additional detail of deposition location. The location of direct manure application through livestock depends on the feeding option, and the associated fraction of time spent in each location (corral, pasture, *milpa*, or common land). It is assumed that manure production is constant throughout the day. Manure production for each sheep group at each location are multiplied by the number of sheep, which is summed across sheep groups to give total manure component outputs for each location.

APSIM is used to simulate: (a) dynamics of manure in an ‘open air’ pile in the corral and (b) the decomposition of manure that is applied to crops, pasture, and common land. This is unlike many crop–livestock models which do not simulate manure dynamics; however Rufino et al. (2007b) described a simple model for manure losses during collection and storage which uses efficiencies to calculate losses of manure under alternative management strategies. Farmer decision making regarding allocation of stored manure is defined in Vensim™. Manure that accumulates in the corral (referred to as the ‘pile’) can be redistributed to the pasture or *milpa*. Manure application is specified by an initial application date and a frequency of application. When manure is used, the pile in APSIM is emptied and manure of specified C and N concentrations is applied to the chosen location.

Urine nitrogen output (Eq. (61)) can also be added to each of the four locations. Volatilized urea is the major urinary end-product of N metabolism (Archibeque et al., 2001). Because APSIM does not simulate volatilization, a specific fraction for each location is used to specify the amount of urine nitrogen lost. Fertilizer urea can also be added to the pasture or *milpa* on specified dates and at specified rates (see Table 1).

2.8. Feed refusals

Unlike most crop–livestock models which assume full utilization of feeds, the integrated model assumes only partial utilization, depending on the feed type. Feed composition values of feed refusals were obtained from a variety of sources (Supplementary material, Table 12). The method used in the model to calculate the nitrogen concentration of feed refusals depends on the ingredient. For milk and commercial supplement, the nitrogen concentrations of the refused fraction (set to zero as default) are the same as that of the feed offered. For Leucaena and native grass, the nitrogen concentration of the refused fraction is defined for each season, and is lower than that of the feed offered. For maize grain, the nitrogen concentration of that refused is variable, but equal to that of the feed offered. For Guinea grass and maize stover, the nitrogen concentration is variable and lower than the feed offered, because in each case a proportion of the stem is not consumed. Maize stover nitrogen is conserved by allocating nitrogen to the leaf and stem components (Eqs. (51)–(52)). Guinea grass nitrogen is conserved through the separation of stem and leaf nitrogen stocks in APSIM.

For ingredients with variable nitrogen concentration, a lower and upper value is defined (Supplementary material, Table 12). The nitrogen fraction of the ingredient is described relative to the limits (Eq. (62)), returning a value between zero and one, enabling the properties of the refused feed to vary according to the quality of the feed offered. Carbon content of the ingredients at the upper and lower limits (Eq. (63)) is a function of the fractions of carbon-containing components in the feed (fiber, lignin, starch, sugar, crude protein, fat) and their carbon fractions (Supplementary material, Table 10). The carbon fraction of each refused feed ingredient (Eq. (64)) is a function of the nitrogen proportion of the refused feed, the carbon content of the feed at the upper and lower limits, and a linear function describing the output response between the upper and lower limit. Feed refusal carbon (Eq. (65)) is calculated for each combination of ingredient and sheep group, and output locations are specified (Eq. (66)) and summed across sheep groups, and across ingredients, to give total feed refusal carbon for each location. An analogous process to that described for carbon is used to determine the feed refusal nitrogen for each location, and the carbon to nitrogen ratio (Eq. (68)) is also calculated.

Like manure, feed refusal that accumulates in the corral can be redistributed to the pasture or *milpa*. Feed refusal application occurs on a signal, simultaneously with dung application.

2.9. Labor analysis

Analysis of labor is a focus of the analysis, because labor is often one of the most limiting resources in smallholder agricultural systems (Norton et al., 2006). This is particularly true for the *milpa*-sheep system due to low population densities and availability of common land. For simplicity, labor allocation decisions in the model are largely analyzed as exogenous. If the labor required each day exceeds that available, labor is hired to meet this shortfall. There is no feedback from this shortage back to management decisions, nor between economic returns to labor and labor allocation. This is consistent with the aim of describing outcomes given management decisions, rather than predicting management decisions. Following traditional patterns of labor allocation described in (Kintz, 1998), we assumed that only the adult male of the household works in the *milpa*, whereas other members of the household may be involved in livestock activities. Values for constants, and ranges for parameters used in the following description of labor analysis are contained in the Supplementary material (Table 13). Available household labor (Eq. (69)) depends on the number of adult workers, the number of additional adult workers available for livestock activities, and the amount of labor provided per adult worker per day. The balance of available labor after livestock labor needs are accounted for (Eq. (70)) is the available household labor minus the required livestock labor. If the livestock labor balance is negative there will be cash expenditure on hired labor (Eq. (71)) at an assumed constant wage rate. If the livestock labor balance is positive, the surplus labor will be available for *milpa* production. This simplification stems from our observation that sheep farmers tend to give priority to livestock over *milpa* labor needs. The household labor available for *milpa* (Eq. (72)), unallocated labor, (Eq. (73)) and expenditure on hired labor (Eq. (74)) are calculated.

2.9.1. Livestock labor

Required livestock labor (Eq. (75)) is the sum of all livestock-related labor requirements, including sheep husbandry, tending to grazing sheep, cut and carry of feeds, applying dung and feed refusals to Guinea grass, and managing the Guinea grass. Sheep husbandry labor (Eq. (76)) depends on the total number of sheep and a non-linear function (Supplementary material, Fig. 1) that assumes diminishing marginal labor needs per additional sheep added. For each location where sheep are present, the labor required to manage grazing sheep (Eq. (77)) depends on the fraction of grazing time that is supervised (based largely on whether or not there are fences), and the daily hours of sheep grazing. For each ingredient fed by cut and carry, labor needed (Eq. (78)) depends on the quantity required and a labor rate for collecting that ingredient. Labor required to apply dung and refused feeds to grass (Eq. (79)) depends on the quantity and a labor rate. Guinea grass management labor (Eq. (80)) depends on the area of Guinea grass cultivated, and a non-linear function (Supplementary material, Fig. 2) that assumes diminishing marginal labor needs per additional unit of land.

2.9.2. Milpa labor

Required *milpa* labor (Eqs. (81)–(82)) depends on the area of *milpa* and the labor rates for various dry season activities (selecting and marking the plot, felling trees, burning) and wet season activities (planting, weed control, bending stalks, and harvesting). Additional labor input may be needed to apply dung and feed refusals to the *milpa*, calculated as for grass. Labor rates for these activities also depend on whether the *milpa* is in its first or second year of cultivation.

2.10. Economic analysis

Similar to the labor analyses, economic outcomes are assumed not to influence management decisions. Costs and revenues are calculated on an enterprise full-income basis, meaning that economic calculations are made separately for livestock and *milpa*, and income is calculated on quantity produced, whether or not it is sold. This is an appropriate method for better describing profitability when products are self-consumed or used as inputs for another enterprise. The two enterprises in the model are *milpa* and livestock (which includes Guinea grass cultivation). Values for constants, and ranges for parameters used in the following description of economic analyses are contained in the Supplementary material (Table 14).

2.10.1. Expenditures

Annual costs of fixed inputs with a useful life of more than one year are calculated for irrigation infrastructure, fencing, improved pasture, corrals, and a storeroom, based on the formulae of Monke and Pearson (1989). Annual costs (Eq. (83)) are calculated on the present value of the salvage value of the asset, the initial cost, the useful life of the asset, and the social interest rate. The present value of the salvage value of the asset (Eq. (84)) is a function of the useful life of the asset, the risk free interest rate, and the future salvage value.

The initial cost of established grass (Eq. (85)) depends on the cost of pasture establishment per hectare and the area of grass. The initial cost of pasture fencing (Eq. (86)) depends on the length of fencing and the fencing cost per meter.

The total annual costs associated with livestock assets (Eq. (87)) and *milpa* assets (Eq. (88)) are sums of the individual annual costs, with a proportional allocation of the storeroom costs to each enterprise. Livestock enterprise expenditures (Eq. (89)) are the sum of flock health, grass maintenance, labor, and feed expenditures, and livestock annual costs. Irrigation expenditure on Guinea grass (Eq. (90)) includes the cost of electricity and equipment repairs and maintenance, and depends on the cost of operating irrigation equipment per hectare, a minimum cost per hectare, and the area irrigated. Flock health expenditures (Eq. (91)) depend on the number of sheep and the flock health cost per sheep. The rate of fertilizer nitrogen applied to grass (Eq. (92)) is defined by specifying the day(s) of year that urea is applied, and a nitrogen application rate. Fertilizer expenditure (Eq. (92)) depends on the area of grass, the price and nitrogen content of urea, and the fertilizer nitrogen application rate. Herbicide expenditure on Guinea grass (Eq. (93)) depends on the area of grass, and the herbicide application rate, frequency of use, and cost. Feed expenditure (Eq. (94)) is the sum of expenditures of all purchased ingredients, including the value of grain and stover purchased from the *milpa* enterprise. Livestock needs are calculated in terms of DM, whereas feeds are purchased on a wet basis. Thus, expenditure for each ingredient (Eq. (95)) is a function of the dry matter purchase rate, the purchase price, and the dry matter fraction of the purchased ingredient.

Milpa expenditure (Eq. (96)) is the sum of fertilizer and labor expenditures, and annual costs. The calculation of expenditure on *milpa* labor has been described above. Fertilizer expenditure on *milpa* is calculated in the same manner as for grass.

2.10.2. Income

Livestock enterprise income (Eq. (97)) is the sum of income from animal and Guinea grass sales. Livestock sales (Eq. (98)) are the sum of sales of finished males, finished females, cull rams, and cull ewes. Sales for each of the livestock groups depend on the weight of livestock sold and the price per kg (e.g. Eq. (99) for finished males). Guinea grass sales (Eq. (100)) depend on the rate of grass sales, the sale price, and the dry matter fraction of the grass. Livestock enterprise net income (Eq. (101)) is the difference between livestock income and livestock expenditures.

Milpa enterprise income (Eq. (102)) is the value of maize grain and stover sold or transferred to the livestock enterprise. The values of grain and stover sales are calculated in the same manner as grass sales above. *Milpa* enterprise net income (Eq. (103)) is the difference between *milpa* enterprise income and *milpa* enterprise expenditures. Total net income (Eq. (104)) is the sum of livestock and *milpa* net incomes.

2.10.3. Labor and management income

Labor and management income is what remains of the household net income after a fair return to the household's equity in capital items and land is subtracted. Typically, labor and management income also includes the value of family labor (Knoblauch et al., 2005). Labor and management income (Eq. (105)) therefore depends on the enterprise net income and the opportunity cost of capital. The opportunity cost of capital for livestock and *milpa* enterprises (Eq. (106)) depends on the current value of assets, and the risk-free rate of interest that could be earned if the farm assets were invested in a savings account. The current value (Eq. (107)) of fixed inputs is calculated by depreciating the initial costs of the asset. The current values for livestock and *milpa* enterprises (Eqs. (108)–(109)) are the sum of all current values for the enterprise.

For simplicity, fixed inputs are assumed to depreciate by an exponential decay that tends towards the salvage value of the asset rather than by a tax depreciation schedule or current market values. Depreciation (Eq. (110)) depends on the difference between the current value and the salvage value, the useful life of the asset, and the number of adjustment times over which the depreciation occurs.

The current value of livestock (Eq. (111)) for each group depends on the total group weight and the price per unit weight. The price for a finished sheep is used for calculating the current value of lambs, young, and finishing sheep. The price for a cull ewe or ram is used for a growing or mature ewe or ram. This is a simplification, and likely underestimates the current value of some groups, particularly quality breeding stock.

The current value of land for *milpa* (Eq. (112)) or grass (Eq. (113)) depends on the area of land and the current value of land per hectare. The current value of stored grain (Eq. (114)) depends on the quantity of grain stored, the wet sale price, and the fraction dry matter of the grain.

3. Discussion

3.1. Model behavior and evaluation

The term 'evaluation' is used rather than 'validation', in accordance with the argument of Sterman (2000) that no model can be validated because all models are simplified representations of the real world, and are therefore wrong. Sterman (2000) suggests seeking multiple points of contact between the model and reality by drawing on a wide range of tests, potentially improving the model through the iterative loop of model building and testing. Model evaluation often involves assessment of the ability to reproduce observed behaviors (i.e. comparison of observed and predicted values). Although this is important, it is insufficient to fully evaluate a model. In this instance it is also unfeasible, because it would be extremely expensive and time consuming to collect the necessary data for a wide range of smallholder crop–livestock scenarios. No extensive time-series data exist for comparison to the modeled system, Even if such time-series data were available, a point-to-point comparison of the model outputs to the data would not be an appropriate evaluation of the model given that the system is probably sensitive to small perturbations that influence the specific time path of the dynamics. The following discussion focuses on the set of model evaluation tests described by Sterman, and gives examples of tests performed and issues considered.

3.1.1. Boundary adequacy

This test considers whether important concepts for addressing the research question are endogenous in the model. For the purposes of the scenarios in the companion paper, important endogenous structure would include crop growth, soil nitrogen and organic matter, livestock dynamics, and manure production. A pertinent issue is the simplifying assumption that common land resources are not limiting.

3.1.2. Structure assessment

Much of the integrated model structure is from existing models (APSIM and SRNS) which have already been subject to evaluation (e.g. Probert et al., 1998; Kinyangi et al., 2004; Cannas et al., 2004, 2006). We assessed the integrated model to ensure that it conformed to physical laws such as conservation of matter, particularly at the interface between APSIM and Vensim™. During the model building process, partial models were assessed for behavior consistent with existing knowledge of the system before being joined to other model structure. An example of this partial model testing is checking for appropriate qualitative response to changing live-weight gain. The response of the number of male lambs to a partial model test where live-weight gain is stepped up from 0.13 to 0.18 kg sheep^{-1} day^{-1} at time 100 is shown in Fig. 4. The time needed to grow a lamb from weaning decreased from

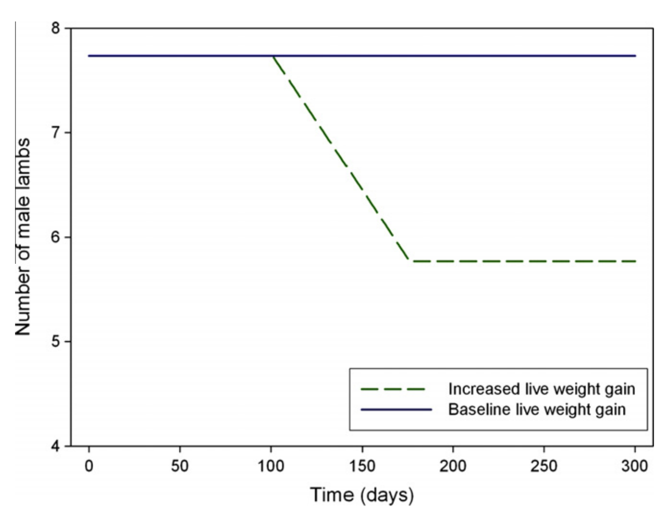

Fig. 4. The effect on the number of male lambs in the flock, of increasing live-weight gain from 0.13 to 0.18 kg sheep^{-1} day^{-1}, at time 100. This partial model test was done with the livestock dynamics decoupled from other parts of the model.

102 days to 75 days. With a constant lamb birth rate, because lambs are maturing more rapidly their number decreases, and by time 176 a new, lower, equilibrium number of lambs has been established. Although a simple example, this partial model test demonstrates model behavior consistent with existing knowledge of stock and flow dynamics.

3.1.3. Dimensional consistency

Dimensional consistency of models involves specifying the units of measure for each variable in the model, and checking for dimensional errors. Vensim™ includes a tool for checking unit consistency of model equations, which we used to ensure unit errors were correct.

3.1.4. Constant and parameter assessment

Data for system dynamics models are often drawn from a broader pool than just numerical data, and may include 'mental data' or 'soft variables' (Sterman, 2000). Values were mainly sourced from literature values and measurement, but also from interviews, observations, and expert knowledge. Although we recognize that using statistical methods to estimate values is preferable, this would require significant cost and effort for the many constants and parameters in our model. Instead, we made a judgment on which constants and parameters were most important for detailed measurement, and focused data collection on these. A model structure, if reasonably correct, can be used through sensitivity analysis to assess which information is most important. This was difficult to do in this case because of computational issues described below.

3.1.5. Extreme conditions

Throughout the model development process we tested the model in response to changes in constants and parameters over a realistic range, including zero values. The model passed extreme conditions tests which included livestock numbers, economic parameters, land allocation, and management options.

3.1.6. Integration error

Because the Vensim™ model is a system of differential equations solved by numerical integration, a time step that is too large can introduce spurious dynamics in the model. Although the time unit and time step of the model were both equal to one, we evaluated time constants to ensure that the shortest time constant was at least twice the time step (Ford, 1999) to reduce potential integration error problems.

3.1.7. Behavior reproduction

These tests involve reproduction of behavior of interest, and are the focus of the companion paper. Partial models were assessed for appropriate behavior, as detailed in the structure assessment.

3.1.8. Sensitivity analysis

Three types of sensitivity are relevant: numerical (when a change in assumptions changes the numerical value of the results), behavioral (when a change in assumptions changes the patterns of behavior generated by the model, and policy (when a change in assumptions changes the impacts of a proposed policy) (Sterman, 2000). Sensitivity analysis with the integrated model was difficult because the time required to run the integrated model is long (depending on the computer processing speed) and the Vensim™ sensitivity analysis tool does not work in conjunction with the APSIM interface. Sensitivity analyses of the labor and economics constants change numerical outputs, but do not change patterns of behavior in the model, because there is no feedback of labor or economics back to management decisions. Changes in other selected parameters were assessed through sensitivity analysis of the full and partial model.

3.2. Key contributions of this modeling approach

The main strength of the modeling approach used is the ability to link a well established crop, soil, and atmospheric modeling package (APSIM) and a ruminant nutrition modeling package (SRNS), with the flexibility to simulate very specific and unique crop–livestock systems using Vensim™. Other characteristics of this modeling approach are significant. The stock-flow structure developed for livestock dynamics tracks both numbers and body weight, and enables analysis of scenarios that affect such parameters as birth and death rates. The stock-flow structure also allows the specification of desired livestock numbers, and uses goal-seeking structure to adjust flock dynamics. The modeling effort is an example of applying the Sterman (2000) approach to model evaluation, which more holistically considers the performance of the model. Lastly, the combination of economic analyses, including enterprise budgeting, consideration of asset values, and labor and management income are not normally included in agro-biological models, and are important and useful methods of scenario assessment.

3.3. Further development of the integrated model

There are a number of areas in which the integrated model could be improved, including issues with using APSIM and SRNS, additional soil types, crop species and spatial diversity, spatial relationship between locations, sub-optimal livestock feed intake, defining feed quality parameters, modeling of additional nutrients, and other issues which are universal to modeling crop–livestock systems. These issues are discussed in detail in Parsons (2008). Such changes may not necessarily result in significant differences, either numerically or behaviorally, in model outcomes. Suggested improvements could be made and formal testing could be done to assess improvement of the model. In the interim, the integrated model is built upon a strong base of existing modeling work, and is a potentially valuable tool for representing crop–livestock systems.

4. Conclusions

Crop–livestock systems, particularly those in developing countries, are myriad and complex, making it difficult for a particular modeling package to be applicable to every situation. However, modeling can be extremely time consuming, and it is typically a poor allocation of resources to start from scratch with modeling any new system (Thornton and Herrero, 2001). The foregoing discusses the development of a crop–livestock simulation model that uses an existing crop modeling software package (APSIM) as the foundation. A module within APSIM allows linkage with Vensim™, an icon-based modeling software package. The strength of this modeling approach is the combination of harnessing the power of a well established crop, soil, and atmospheric modeling package with the flexibility to simulate very specific and unique crop–livestock systems. With appropriate modification, this method could be applicable to modeling a wide range of crop–livestock systems. The companion paper describes performance of the model in examining outcomes of differing scenarios of crop–livestock integration in Yucatán.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.agsy.2010.07.006.

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