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Development of an Agent-Based Epidemiological Model of Beef Cattle

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We developed an agent-based epidemiological model of animal disease propagation within the beef and dairy industries in context of a consortium of interested parties including the New Mexico State University (NMSU) Extension Service, the New Mexico Livestock Board (NMLB), ranchers representing the beef industry, and farmers representing the dairy industry. The model requires a thorough understanding of the life cycles for commodity livestock, especially the transportation and mixing of present commercial production. The model allows us to better understand how inter-operation transfer of livestock can impact the likelihood, magnitude, and geographic dispersal of infectious disease outbreaks. This will aid us in assessing the cost-effectiveness of current and proposed prevention, monitoring and mitigation strategies. Our initial model focuses on the propagation of bovine tuberculosis (TB) in beef cattle. In subsequent work, we will expand the computational model to include dairy cattle, as well as other diseases such as foot-and-mouth disease (FMD) and Rift Valley fever.

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1.1 The Current Situation for TB Management in New Mexico

Between 2005 and 2008 the USDA categorized New Mexico with split-state status: the majority of the State accredited TB free, and a small region (encompassing parts of Curry and Roosevelt counties) Modified Accredited Advanced, which places testing requirements on the movement of cattle. In September 2008 the USDA downgraded the entire state to Modified Accredited Advanced. New Mexico then applied to USDA for a return to split-state status, which the USDA recently accepted. This downgrading of New Mexico's TB status gave rise to a variety of complicating logistical hurdles,[1] exerting limitations on dairy farms and cow-and-calf ranches in their management and marketing. The Consortium is interested in evaluating existing and proposed policies in order to minimize the likelihood of a TB outbreak and thus protect its TB-free accreditation.

Possible better strategies for TB control might include:

1) Improved disease detection;
2) Improving geographic protocols for dealing with disease outbreaks;
3) Segregation of rodeo cattle from the native population;
4) Incentives promoting closed herd management; and
5) Improved oversight on marginal operators.

1.2 Goals of the Modeling Effort

This model has the capacity to rapidly run a wide variety of outbreak scenarios. Through this investigation, we will be able to determine which pathways and practices and scenarios are the most damaging, as well as the most robust. We are especially interested in uncovering surprise scenarios– "black swans" –as well as any risk factors not previously considered. With this model we will be able to:

- Measure the consequences of credible animal disease outbreak scenarios
- Evaluate the efficacy of disease monitoring and prevention policies
- Evaluate the effectiveness of a variety of protocols for outbreak mitigation, such as
    - Restrictions on animal movements across state and international borders
    - Quarantines
    - Ring-vaccination
    - Herd de-population
    - Disease testing
- Perform virtual trace-back from the first detection of diseased animals to delimit the point of disease origin and those operations that have been exposed[2]

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[1] Logistical constraints included: (1) expense of TB testing; (2) temporal constraints– a lesion must be read three days later, and many cow-and-calf operations do not have facilities to hold and feed animals for three days; (3) many operations cross state boundaries, affecting animal movements carried out by a single operator; and, (4) the testing requirements vary from one state to another resulting in a patchwork quilt of regulation.

[2] *Virtual* trace-back can assist in identifying monitoring and information sharing that would best allow *actual* trace-back.

- Perform virtual trace-forward from point of disease origin to identify the operations and population of potentially exposed animals[3]

We intend to provide a policy tool to evaluate transmission of infectious disease in the cattle industry to inform the NMLB's management and oversight policies for disease prevention and proactive strategy implementation, especially those which provide incentives for industry participants to enhance bio-security without added regulation.

1.3 Process

This model serves as an ideal example of the utility of participatory development. In comparison to classic analysis, the analysts work in tandem with clients. The client team (The Consortium) provides direction and domain expertise, while the modeling team (SNL) provides facilitation and technical expertise in modeling and analysis. This approach enhances team learning, fosters consensus, and connects key stakeholders to results of the analytical effort (Vennix, 1996).

Model building provides an opportunity to structure discussion and foster an environment conducive to testing assumptions and strategies (Vennix *et al.*, 1997). The impact of computer models on policy making appear primarily conceptual rather than instrumental. With increasing complexity individual team members come to problems with niche perceptions of whole problems. Group developed models expand and connect these perceptions, aiding identification of courses of action that team members will feel confident and committed to.

Over the last 30 years, a strong literature basis grounded in applied research has been established to guide this modeling approach (Rouwette *et al*., 2002). Individual practices range widely, but most have three elements in common: the notion of *teamwork* to tackle the different and often competing roles necessary to carry out a successful project (Richardson and Andersen, 1995); the use of specific protocols to achieve different purposes throughout the process –these have come to be referred to as *scripts* (Andersen and Richardsen, 1997); and the sequencing of steps– iterated as needed– until the client team is satisfied and has been able to learn enough from the exercise to take the next step toward decision making and implementation.

A full-blown modeling exercise includes the following phases:

1) Problem identification and definition
2) Model conceptualization
3) Model formulation and simulation
4) Model testing and evaluation
5) Model-based problem analysis and policy experimentation
6) Understanding and discernment
7) Policy implementation (action) and outcomes

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[3] *Virtual* trace-forward is a means by which we can measure consequences and evaluate strategies using the model, extracting lessons and insights that can then be generalized to the *real* system.

Some of these phases do not involve the client team directly. The working meetings with the Consortium, on October 28 and December 15, covered the first two steps. The modeling team is currently focused on steps three, four, and five.

The outline above, describing a full blown group modeling effort, disguises the significant iteration required in the modeling method, particularly the back-and-forth required between the modeling and client teams to ensure that the analytical effort adequately reflects their concerns. Assumptions embedded in the computational model must be systematically checked by the subject experts in the client team. Client participation may vary from project to project, depending upon the group's interest in involvement. We recommend at minimum three half-day face-to-face meetings between the modeling team and as many of the key stakeholders from the client team as possible.

The first meeting elicited the client team's input on problem definition and model conceptualization. A follow-up meeting to demonstrate a running model for chauffeured problem analysis and policy experimentation would assist in applying model analysis to specific client concerns. To ensure the model is ready for such a meeting other forms of iteration will be required with a subset of the client team,[4] as well as exchange of written information (partial report drafts) with the larger group. Based upon the feedback received from the client team, more work can be done to expand the model, refine it, calibrate it, or otherwise prepare it for more extensive application and to build confidence in the model (e.g. validation).

A final meeting is scheduled at this point, where the model is used by the client team, with assistance by the modeling team, to communicate conclusions to others, and to articulate justifications for decision making or policy change. This synthesizes the understanding and discernment achieved via the model and serves to kick-off the implementation process – translating learning into action.

This paper contains a detailed description of the conceptual model elicited from the Consortium, a discussion of the attributes of bovine TB, and the detection, prevention and mitigation policies currently in place, as well as a characterization of the first phase of the beef computational model and some preliminary results from simulations. We conclude with an outline of the next steps.

2 Beef Cattle Conceptual model

The physical beef cattle production system consists of five major components: (1) cow-and-calf ranches, (2) stocker operations, (3) feedlot operations, (4) meat-packing plants, and (5) sales barns (physical markets where cattle mix in the process of being bought and sold). This system and the major routes of animal movement through the system are depicted in **Figure 1**. The lifespan for feeder cattle between birth and slaughter is nominally about eighteen months. This lifespan is divided roughly equally between time spent on ranches, in stocker operations, and on feedlots. In the following sections we use this figure as a guide to describing the cattle movements within and between each of the five major components of the beef cattle life path.

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[4] One example was the conference call held on December 15, 2009.

Rodeo cattle are included, even though their numbers are extremely small in relation to the number of beef cattle, since they may add significantly to the risk of exposure to bovine TB.

2.1 Cow-and-Calf Ranches

Cow-and-calf ranches are at the head of the feeder cattle supply chain. New Mexico contains about 1,700, varying in size from hobby ranches up to ranches as large as 10,000 head. An average cow-and-calf ranch in New Mexico will have between 100-200 cows; tiny ranches have as few as 40 cows.[5]

These ranches are widely dispersed throughout the state on both public and private rangelands with grasslands sufficient to support grazing. Cow-and-calf operations use a breeding stock of cows (and a few bulls[6]) to birth calves for beef. Cow-and-calf operations are relatively self-sufficient. The rangelands provide low-cost forage for the breeding stock. Under a closed herd management system, a substantial number of the female calves are retained as replacement heifers to replenish the breeding stock as imported cattle sometimes do not acclimate well – especially if the terrain is unfamiliar and challenging. Bulls are commonly bought or traded among ranchers to provide genetic diversity. Under favorable range and economic conditions, heifers and breeder cows might be purchased to promote herd expansion. (Most likely these heifers would be purchased from a stocker operation. The breeder cows would be purchased from another cow-and-calf operation.) In **Figure 1**, the black recursive arrow, coming from the cow-and-calf ranches and going back into it, represents the trading of bulls, breeder cows, and heifers between cow-and-calf ranches. The magenta arrow from stocker operations to cow-and-calf ranches represents purchase of replacement heifers backgrounded at a stocker operation. This backgrounding of animals can increase the risk of spreading foreign animal diseases due to mixing of animals between herds.

New Mexico’s 460,000 beef cows produce about 340,000 beef calves each year.[7] A heifer usually births her first calf at age two. Each cow will typically produce six to eight calves over its lifetime. Most beef cows are culled from the herd at about ten years of age. Therefore, about ten percent of the beef cow population is culled each year. To avoid absorbing the cost of transportation most ranchers sell their culled animals in sales barns, which tend to be within a 50-mile range, rather than directly to feedlots or meat-packing plants, which are 500+ miles away. About 80-90 percent of the culled animals go directly to meat-packing plants, while the remaining 10-20 percent are first placed in specialized feedlots to be fattened. Seasonal market fluctuations affect these percentages.

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[5] New Mexico ranch sizes deemed small, medium, and large, hold approximately 125, 225, and 325 cows, respectively (Conference call, 12/15/2009).

[6] A single bull typically can service as many as about twenty cows.

[7] Using the reference value of 460,000 beef cows and a System Dynamics model, we estimated the numbers of all other animals (calves, bulls, etc.), as well as the numbers of annual births, deaths, slaughter rate, etc. This work, described in detail in Appendix 1, also indicates a retention rate of about 40 percent of the female calves for the purpose of replenishing the breeding stock.

The majority of calves are birthed in the spring. Aside from the females retained as replacement heifers, these calves are sold in the fall between six and nine months of age to stocker operations. In New Mexico these sales peak in early October. Occasionally, young calves (3-4 months of age) will be backgrounded at specialized feedlots prior to being run on a stocker operation. The orange arrows in **Figure 1** represent this transfer, which is discussed in more detail in the section of this report dealing with feedlot operations.

2.2 Markets

Cattle are sold in one of three ways: (1) at sales barns; (2) through country buyers; and, (3) via virtual markets – video auctions carried out over the internet. In New Mexico, cattle sales are distributed roughly equally among these three methods – about one third each. Almost all feeder calves are sold. However, once purchased from cow-and-calf ranchers, the majority of the calves will have the same owner throughout the rest of their lives, until they are slaughtered. The further the cattle move through the feeder cattle aging chain, the greater the likelihood of retained ownership, as well as the greater the proportion of direct sales (as opposed to auction-mediated sales).

2.2.1 Sales Barns

Eight livestock sales barns operate in New Mexico.[8] Sales occur weekly and handle a variety of animal types. Some handle mostly calves and culled breeder cows; others specialize in dairy cattle, while others are more general purpose. Some handle far more animals than others and attract higher-volume buyers. The particular sales barn a cattle owner selects to market his cattle depends on a variety of factors, including the convenience of transportation logistics and the number and types of buyers that are expected to attend.

Animals from throughout the region come together at a single location on a specified day of the week to be auctioned. Those confined in adjacent pens may come into close contact with one another. Animals may be aggregated or sorted to shape the loads offered for sale. For example, 500-pound calves are often aggregated into lots of 100 animals – the number that can be transported on a single cattle truck. As animals are sold, they are shipped off to new locations to mix with other animals at the purchaser’s operation. This sales-barn mixing process may facilitate the spread of foreign animal diseases, such as bovine TB. Explicit consideration of the mechanics of animal contact at the sales barns within the systems-level agent-based model provides a practical means to investigate this hypothesis. For this reason, **Figure 1** distinguishes two possible physical paths between operations, one direct and the other via a sales barn.

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[8] At Farmington, Clayton, Belen, Los Lunas, Clovis, Portales, Roswell, and Deming.

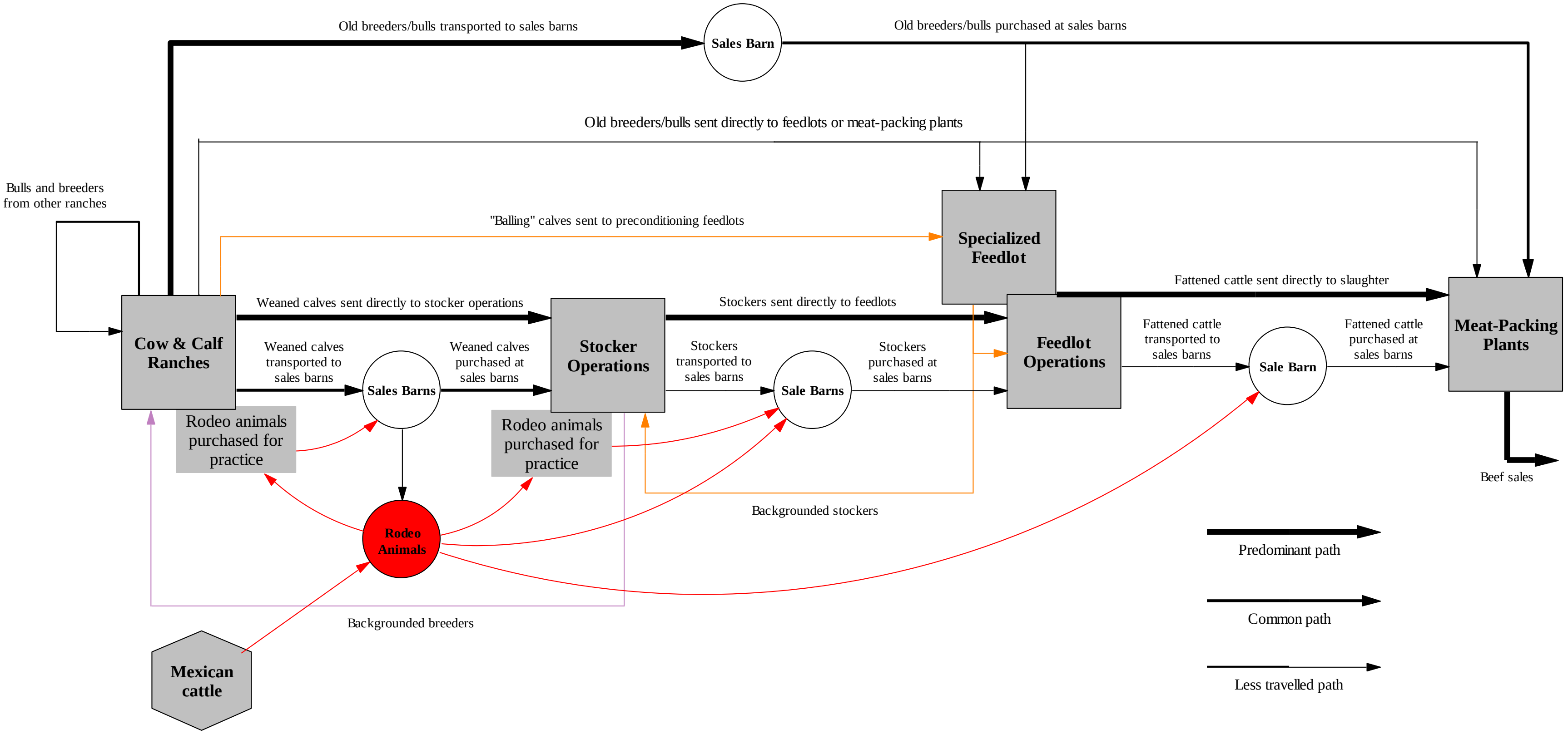

Figure 1. A conceptualization of the beef cattle life cycle.

2.2.2 Country Buyers

Country buyers negotiate directly with the ranchers for sales of their cattle. They tend to be high-volume buyers for large feeder cattle growing operations. As they purchase animals, the buyers aggregate and shape the loads. In this process, animals are purchased and relocated without the comingling that occurs at sales barns.

2.2.3 Virtual Markets

In this method of sales, ranchers sign consignment contracts with internet livestock brokering companies. A representative of the brokering company goes to the ranch, inspects the animals, films them, shapes the loads, and writes up a description. The brokerage presents the video via TV and internet and potential buyers place bids over the phone or internet. Like sales-barn operations, the animals are sold by auction – albeit an auction with a larger reach. However, like direct sales via a country buyer, the animals are sold and relocated without the comingling that occurs at sales barns.

2.3 Stocker Operations

The feeder calves purchased from the cow-and-calf ranches are typically grazed on a stocker operation before being sent to the feedlot. Stockers are steers and heifers that are too light for the feedlot and too heavy to be consuming milk from the cow. Usually animals enter the program when the calf weighs 450 to 600 pounds, and they are removed when they reach a weight between 750 and 900 pounds.[9] Most regional stocker operations are located in the Texas panhandle and in northeast New Mexico where grass is plentiful. The yearlings typically graze on some combination of grass, wheat, and/or wheat stubble.

The backgrounding of calves on a stocker operation provides a means to “frame out” the animals using low-cost, high-quality forage. It also provides a training period for trough, readying cows to gain weight on a feedlot’s concentrated grain-based diet (aka “full feed”).[10] Properly backgrounded calves have been shown to gain weight faster and have fewer incidences of disease and injury.

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[9] Weights vary according to frame size, which in turn are affected by breed and gender. Animals of both genders will be mixed-clustered in groups of uniform size when they are transported and sold, and when they are penned in feedlots. Males grow faster and attain a greater final weight than females. Therefore, females transition later than males (from cow-and-calf ranches to stocker operations, to feedlots, etc.). Similarly, males will be slaughtered at a younger age than females. Finally, at the meat-packing plant, animals that fit specifications for both frame size and weight are more valuable (in dollars per pound). There are financial penalties for animals that are too big and do not fit in the “box.” The Consortium advised us to use the following transition weights:

- 450-550 (or up to 600) pounds between cow-calf ranch and stocker operation; heifers being a month or two older and weighing about 50 pounds less than steers;
- 750-900 pounds between stocker operation and feedlot; and
- 1,100-1,250 pounds between feedlot and meat-packing plant.

[10] The calves’ final stage of weaning lasts about 45 days, a period during which they are confined “to doctor;” i.e., have their diet changed to adapt their intestinal bacteria to concentrated feeds.

The length of stay at the stocker operation can vary anywhere between four and twelve months – typically shorter on wheat forage, longer on grass. Time spent grazing is also somewhat determined by the quality of the pasture (rain) and the price of grain. When grain is expensive and pasture is available, the stockers spend more time on pasture. When grain is inexpensive and pasture is scarce, the animals are transitioned to full feed sooner.

At the stocker operation, cattle are configured into groups of 200 based on similarities in size and frame. (This increases mixing in stocker operations.) The animals remain in their cohort group of 200 as they transition from the stocker operation to a feedlot, and thereafter, through to slaughter.

2.4 Feedlot Operations

Grain based “Full Feed” at feedlots encourages rapid weight gain. Beef cattle typically spend between 150 to 180 days on feed to achieve desired slaughter weight. Each group of 200 is penned together. These animals are confined adjacent to neighboring pens of animals, perhaps sharing water troughs and allowing nose-to-nose contact.

Feedlots are efficiency driven, oriented towards bringing each group of cattle to the same desired slaughter weight at the same time, as quickly and as inexpensively as possible. For feeder cattle, grading out at about “70-percent choice” is the current break-even point. That is, if more than 70 percent of the animals grade out at choice, then the producer can turn a profit.

Feedlots tend to be specialized. The larger feedlots specialize in feeder cattle. Smaller feedlots will feed old cattle. Feedlots are located predominantly to the east of New Mexico. Beef cattle move toward the Corn Belt as they age, to be closer to grain feed.

Until recently, feedlots were considered terminal destinations; all cattle placed in them would go directly to slaughter. It was only in the last four to five years that Texas feedlots, for example, started feeding breeding cattle. Some cow-and-calf ranchers sell their calves young, at three to four months of age, to a “preconditioning” feedlot (such as the one in Tucumcari). These are called ‘balling” calves (see orange line in **Figure 1**). Once these calves reach the normal transition weight of 450-600 pounds, they are backgrounded in stocker operations (see accompanying orange line labeled “backgrounded stockers”).

2.5 Meat-Packing Plants

Meat-packing plants are now far larger than in the past, though much less numerous. Plants specializing in the packing of feeder cattle are located in Texas, Kansas, Nebraska, and Colorado. Price incentives influence the movement of cattle. The demand for beef and the flow of fat cattle to slaughter remain relatively constant over the course of the year. To meet demand meat-packing plants operate at close to full capacity, while variations in the length of stay at stocker operations and feedlots effectively spread the bulge of feeder calves birthed every spring into a steady flow of cattle by the time they reach the meat-packing plants. Culled cows and bulls are sent to plants specializing in the production of ground beef and beef for processed foods.

2.6 The Special Case of Rodeo Cattle

Even though the population of rodeo cattle is extremely small relative to regular cattle, it has been hypothesized that they may present a special threat.

Rodeo cattle have several attributes that increase the propensity of spread of bovine TB. A number of the animals, particularly roping steers, are imported from Mexico, with a significantly greater incidence of the disease. These animals live five years or more; enough time for the disease to set in and for increased shedding to occur (see **Figure 5** on page 19). They travel from one community to the next, possibly intermingling with native cattle. At the end of their sporting careers, potentially contagious animals are introduced to the main pipeline to be sold, fattened, and slaughtered in the United States.

However, professional rodeos are run by contractors who provide all of the animals. They tend to specialize in rodeo cattle and normally do not raise beef cattle. Therefore, in general, rodeo animals graze in their own ranches and are penned separately. Specialized cow-and-calf ranches raise bucking stock. Some domestic production of the roping steers is developing, although most are still imported. Once retired, most rodeo cattle are sold terminally, for slaughter. Even though they may be sold in sales barns, their numbers will be very small relative to total sales.

Figure 1 depicts the intermingling between rodeo cattle and native cattle. Mexican cattle are imported to become rodeo animals; domestic animals are purchased at markets for rodeo use. It could be that the main danger of introduction of TB from rodeo cattle into cow-and-calf ranches and stocker operations is in the small number of retired rodeo roping steers *bought for practice* by adults and children residing in these ranches. They are likely to comingle with cattle raised by these ranchers/operators. If the rodeo animals are sick, the disease is likely to be advanced, and they will be highly contagious.

Because of this hypothesized link between rodeo cattle and an increased risk of bovine TB in beef and dairy animals, rodeo cattle are required to be tested annually in New Mexico. However, if the animals are sold privately, or within the same district, they are unlikely to be subject to inspection.

3 Bovine Tuberculosis Attributes and Policies

The TB bacterium is transmitted primarily via aerosol and direct nose-to-nose contact. TB is thought to be able to survive longer in dark, moist environments.[11] It is a progressive disease – as animals become older, they lose the ability to keep the TB organism in check. Due to this, the rate of disease shedding increases over time. **Figure 5** provides a notional representation of the shedding rate as a function of the length of time since the disease was contracted.

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[11] It has been hypothesized that TB can be transmitted via cattle trucks. Unless trucks are disinfected between shipments, TB mycobacterium may be transmissible from one truck load of cattle to the next.

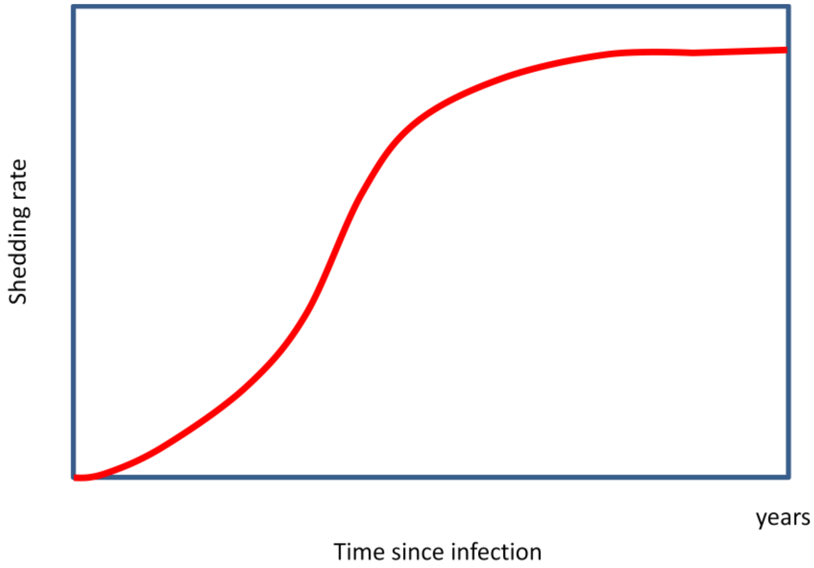

Figure 5. A notional representation of the functional relationship between time since infection and the TB shedding rate.

There are three methods of animal testing:

1) Slaughter surveillance – lung tissue examination. Only older animals with extensive lung scarring will be identified here. These animals have carried the disease for a long period of time and are the most prevalent shedders. The majority of TB detections occur during slaughter surveillance.
2) Whole herd / regulatory testing – usually occurs as the result of trace-back from an animal detection.
3) Stream-of-commerce testing – based on movement and/or sales, especially for those occurring across state lines.

If an animal is confirmed to have the disease, its trajectory is traced back to the animal's point of origin. All of the animals in the ranches (or dairy farms) associated with the diseased animal are tested. Other animals found to contain the disease are removed. This process is repeated until no animal in these locations is found to be sick. (If warranted, this process can be expanded to other operations where these sick animals have been placed, until the disease is stamped out.) In some cases, where the animals graze freely and where there are no conditions for holding and feeding them for three consecutive days, the testing is deemed to be prohibitively expensive.

It is especially important to protect beef cattle breeder stock against contracting TB. These animals live long enough for the disease to progress to the point of significant shedding. The presence of significant shedders can stimulate spread of the disease. It is therefore hypothesized that any activities which increase the contact between potentially diseased animals and the beef or dairy breeder cattle should be discouraged.

4 Summary

Our model depicts this existing system of beef cattle production – replete with extensive comingling and inter-operation transfer of animals –in an agent-based system for the purpose of better understanding the underlying mechanisms which control the spread of foreign animal diseases through discrete geographically dispersed locations. It is anticipated that insights from the modeling exercise will lead to the development of improved disease management policies. In summation:

1) The commercial beef cattle production system provides many opportunities for healthy animals to become exposed to TB though direct contact with animals already carrying the disease.
2) It is especially important to protect breeder cattle against contracting TB because these animals live long enough for the disease to progress to the point of significant disease shedding. It is postulated that any activities that increase the contact between potentially diseased animals and the breeding stock should be minimized.
3) Rodeo cattle have several attributes that may enhance the risk for bovine TB contagion. It is postulated that any activities that allow rodeo cattle to intermingle with native cattle should be discouraged.
4) The NMLB has regulatory authority to protect the integrity of New Mexico’s livestock industry, which includes oversight over cattle operations. They are interested in better understanding the mechanisms underlying the propagation of diseases, and they intend to use that knowledge to enhance cattle management and movements such that:
    a. The likelihood of an outbreak and the spread of a foreign animal disease can be minimized, and
    b. The occurrence of bovine TB within the state can be minimized, thereby protecting New Mexico’s TB-free accreditation status.

5 Phase 1 Agent Based Computational Model

In the first phase of model development, we simplify the system and implement only the major flows along with the associated visualizations of results through plots and other graphical depictions. Once this base model had been built and rigorously tested we continued on to expand its functionality.

Figure 6 depicts the simplified conceptualization of the beef cattle life cycle, as implemented in Phase 1 of the agent-based model. It tracks the path of feeder cattle from birth through its three major life stages – on the cow-and-calf ranch, stocker operation, and feedlot – through to slaughter. It also tracks breeder cattle’s time on the ranch until they are eventually culled from the herd and sent to slaughter. Additionally, the model allows for some exchange of cattle from one cow-and-calf ranch to another.

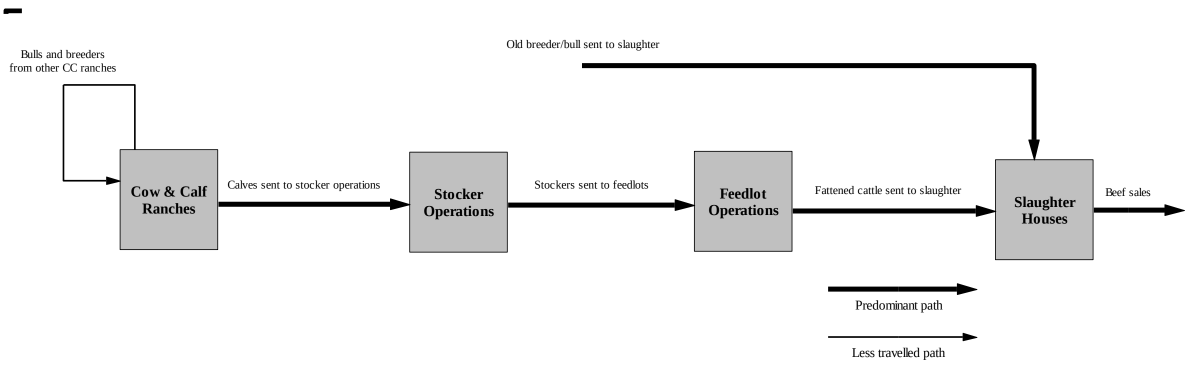

Figure 6. A simplified conceptualization of the beef cattle life cycle as implemented in Phase 1 of the agent-based modeling effort.

5.1 Network of Operations and Transfer of Cattle

The model generates a specified number of each type of operation with size given by a uniform distribution between plus or minus ten percent of the average size. These operations are then randomly distributed within a geographical domain. Operations are then connected by finding a given number of upstream operations that are located nearby. In this way, meat-packing plants are connected to feedlots, feedlots to stocker operations, and stocker operations to cow-and-calf ranches, based on proximity. This base network is used as the primary route for the inter-operation transport of animals.

The shipment of animals is modeled as a push from cow-and-calf ranches to stocker operations, and then a pull from meat-packing plants to feedlots to stocker operations. A push means that when animals are ready to be sold they are binned for a given length of time and then are sold downstream. A pull means that an operation works to be filled with a given number of animals and, when that falls below the size of a shipment, they look upstream for operations that have shipments of the animals with the correct weight to sell. If the operations within the primary network cannot satisfy a given operation’s need to either push animals out or pull them in, operations outside of the network are selected at random until the operation’s need is met.

Whether the transfer is a push or a pull can be modified as can the logic for the creation of the primary network. Additionally, the primary network can be replaced with a different logic for the shipment of animals.

5.2 Cow-and-Calf Ranches

Cow-and-calf ranches are populated with breeder cows and bulls that produce calves at a given rate. These calves stay on the ranch for an average of six months and weight of 600 pounds, after which they are pushed to stocker operations once every 14 days. Link preference is given based on the shortest distance from stocker operations to cow-and-calf ranches. If the stocker operation cannot accept the calves because it is at capacity, another out-of-network stocker operation is randomly chosen to accept the calves. This process is continued until a stocker operation is found that can accept the shipment without going over capacity (defined as ten percent over its desired number of animals).

Cows go through the cycle of impregnation, bearing and birthing a calf, followed by a 60-90 days fallow period nursing their calf, after which they are available to be impregnated at a specified rate.[12]

Once bulls and cows reach an average age of ten years (3,650 days), they are culled and shipped directly to the meat-packing plant. For every breeder that is to be culled, a weaned male or female calf is set aside at the cow-and-calf ranch, for the purpose of replacing the bull or cow, 270 days prior to their disposal.[13]

Cow-and-calf ranches obtain breeding stock from other ranches through the shipment of a specified number of animals from one ranch to another with a given probability of occurrence. Adjacent cow-and-calf ranches can also share fields for a given length of time at a given probability of occurrence. These last two processes create mixing across cow-and-calf ranches and provide for the out of "trunk" spread of an infectious disease.

5.3 Stocker Operations

When below their maximum capacity, stocker operations accept shipments of 600-pound calves pushed to them from cow-and-calf ranches. These calves grow at a rate of 1.67 pounds per day. When they reach a weight of 900 pounds, they are grouped into lots of 200, at which time they are made available for downstream feedlots.

5.4 Feedlots

When they are below their maximum capacity, feedlots pull animals available from stocker operations in groups of 200. These animals arrive at weights near 900 pounds. They gain weight at a rate of two pounds per day. When a group reaches average weight of 1,250 pounds, they are made available to downstream meat-packing plants.

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[12] To the best of our knowledge, the normal fertility rate in the beef industry is 75 percent per year (although some operations claim a fertility rate of 90 percent or more). Therefore, we assume that about 25 percent of cows fail to impregnate in any given year. Assuming no seasonality (something that must be addressed later) and 100,000 cows, about 56,250 cows are pregnant at any given day (100,000*0.75*9/12). This is because the gestation period is equal to nine months. The result is a delivery rate of about 205.5 cows per day [56,250/(9/12)*365]. We also assume that these cows rest between pregnancies (maybe for two months or so). Therefore, about 12,500 cows are "resting" at any given time (100,000*0.75*2/12). To maintain "steady state" (assuming no seasonality), the same number of cows must be impregnated every day. We know that, if a quarter of the cows will skip a year (25,000), than the 205.5 conceptions per day must result from the 6,250 cows remaining (100,000-56,250-12,500-25,000); this results in a "net" impregnation rate of approximately 3.3 percent per day (205.5/6,250). If we account for all of the 31,250 cows that are available to be impregnated at any given time, then the "gross" fertility rate is lower, equal to roughly 0.65 percent per day (205.5/31,250). We further assume a normal distribution around this value, with minimum 0.4 and maximum 0.9 percent per day. We also use a normal distribution for the resting period of two months, plus or minus one month. Finally, for simplicity sake, we assume that the gestation period is invariant.

[13] Calves are weaned at the age of six months. Heifers are ready to reproduce at the age of 15 months. Therefore, arrangements for replacements have to be made nine months in advance (9x30days=270 days). For simplicity sake, we assume the same for steers that are kept to replace bulls.

5.5 Meat-Packing Plants

Meat-packing plants slaughter animals at a fixed rate balanced against the impregnation rate in cow-and-calf ranches so that the number of cattle within the system reaches a quasi-static equilibrium. When a plant runs out of animals, they pull a group that is available from a feedlot (200 animals).

5.6 Infection

Infection is initialized at a random facility in the system. Each type of facility has a different contact rate based upon the transmission rate of tuberculosis and relative mixing rate at that specific type of facility. Infection events occur in facilities with infected cattle based upon this contact rate, mixing rate, and the number of cows infected. As cows move out of the facility, the likelihood of an infected cow being transferred is calculated based upon the percentage of infected cattle in the selling facility. Every day, each facility with an infection is added to a list, as well as all the connections between facilities for thatday. This data can then be stochastically analysed to determine patterns of disease transmission and relative probabilities of source and end state of infected cattle for trace-back and trace-forwards respectively.

6 Model Demonstration

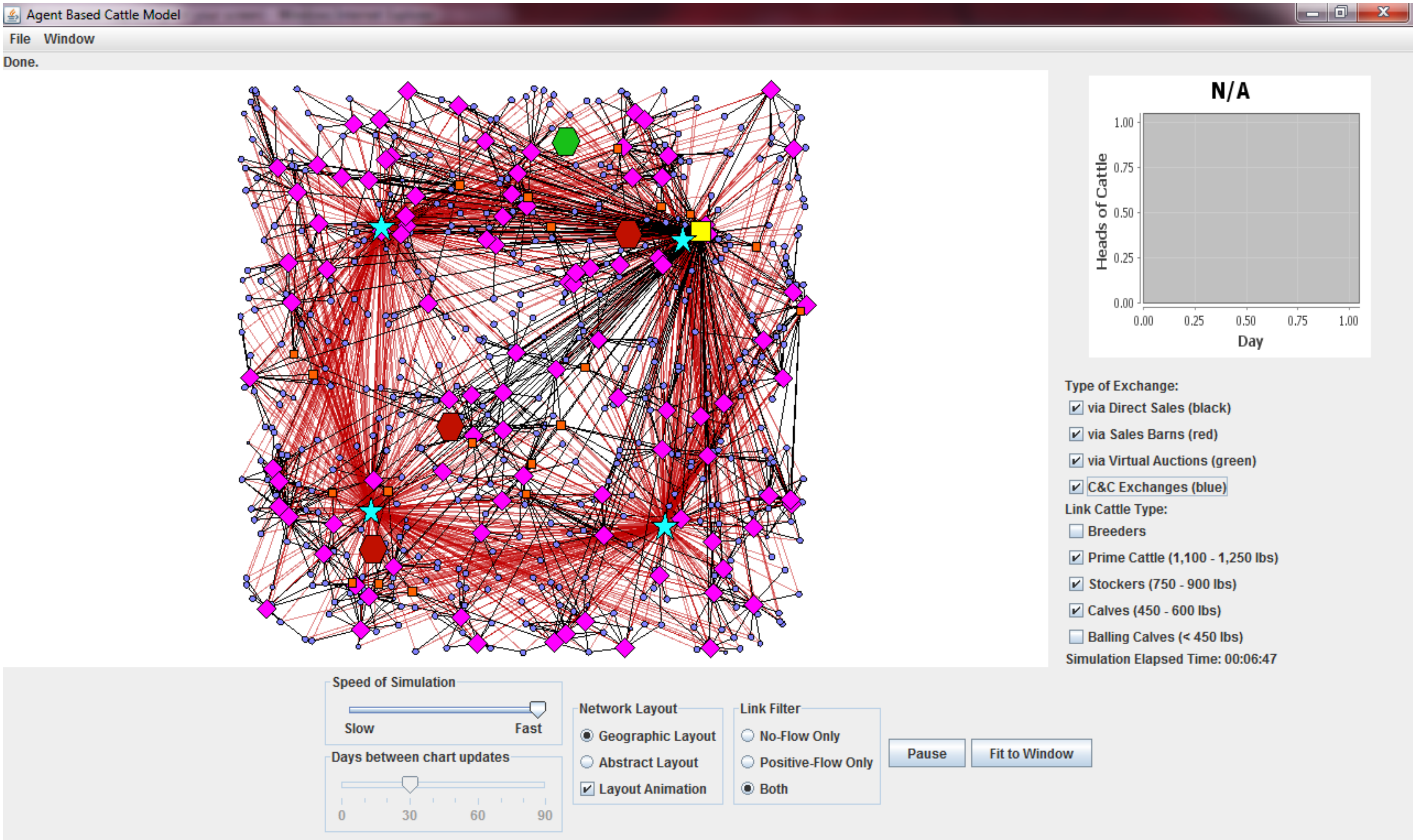
6.1 Interface

The interface of the agent-based model is displayed in **Figure 7**. In order to first check the operation of the model and to provide an understanding of the behavior of the system, we have implemented a graphical interface that draws the network of primary inter-operation transfers and then, as a simulation progresses, shows transfers of cattle between two operations as a link that appears for a short period of time. At the end of the simulation, the transfers of all animals between operations are shown as links, the width of the link denoting the total number of cattle that were transferred between the operations over the period of the simulation.

Total numbers of cattle within each type of operation and across all operations are plotted against time on the left-side graph. On the right, total numbers of cattle within a particular operation are plotted against time as we move the cursor over a network node (operation). Alternatively, by hovering over a link connecting two operations, a plot of shipment size against time is shown.

6.2 Example Simulation

The example simulation uses the following variables: 8 years; no exchanges between cow-and-calf ranches (and no sharing of fields); 100,000 cows; 500 cow-and-calf ranches with an average of 200 cows in each; 100 Stocker operations with an average capacity of 300 cattle; 20 Feedlots with an average capacity of 1,500 cattle; and 2 meat-packing plants with an average capacity of 200 animals and a slaughter rate of 200 animals per day (much greater than what can be supplied.)



Type of Exchange:

☑ via Direct Sales (black)

☑ via Sales Barns (red)

☑ via Virtual Auctions (green)

☑ C&C Exchanges (blue)

Link Cattle Type:

☐ Breeders

☑ Prime Cattle (1,100 - 1,250 lbs)

☑ Stockers (750 - 900 lbs)

☑ Calves (450 - 600 lbs)

☐ Balling Calves (< 450 lbs)

Simulation Elapsed Time: 00:06:47

Network Layout

● Geographic Layout

○ Abstract Layout

☑ Layout Animation

Link Filter

○ No-Flow Only

○ Positive-Flow Only

● Both

Figure 7. Interface of the agent-based model

6.2.1 Network of primary shipments

Full network with nodes situated geographically is shown in the interface (per **Figure 7**). A blow-up of a portion of a geographic network is shown in **Figure 8**.

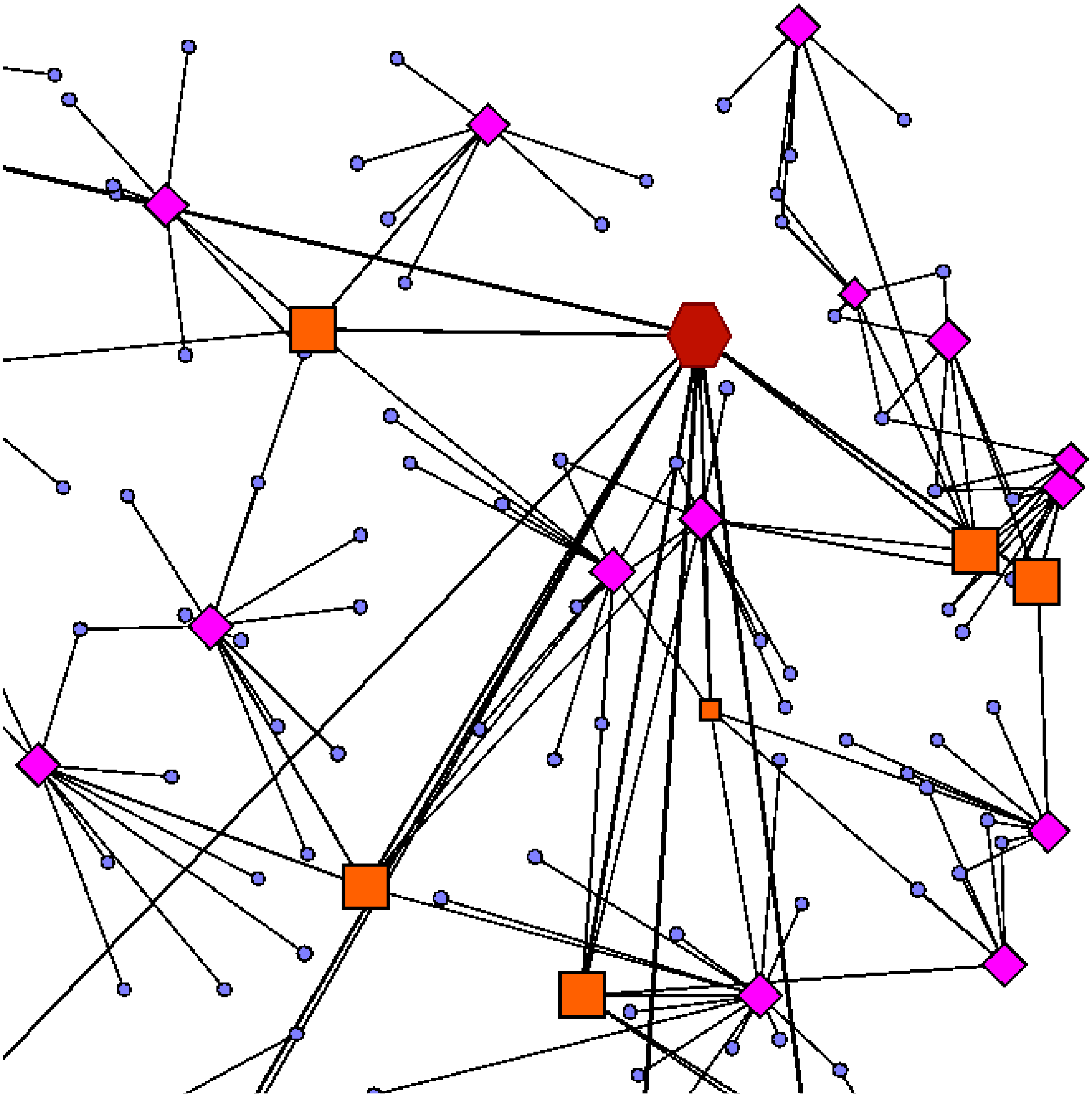


Figure 8. A blow-up diagram of portion of a geographic network

The network in Figure 7 can also be visualized as an “abstract” network that removes geographical orientation of operations and focuses solely on their relationships to each other. This abstract network is shown in **Figure 9**.

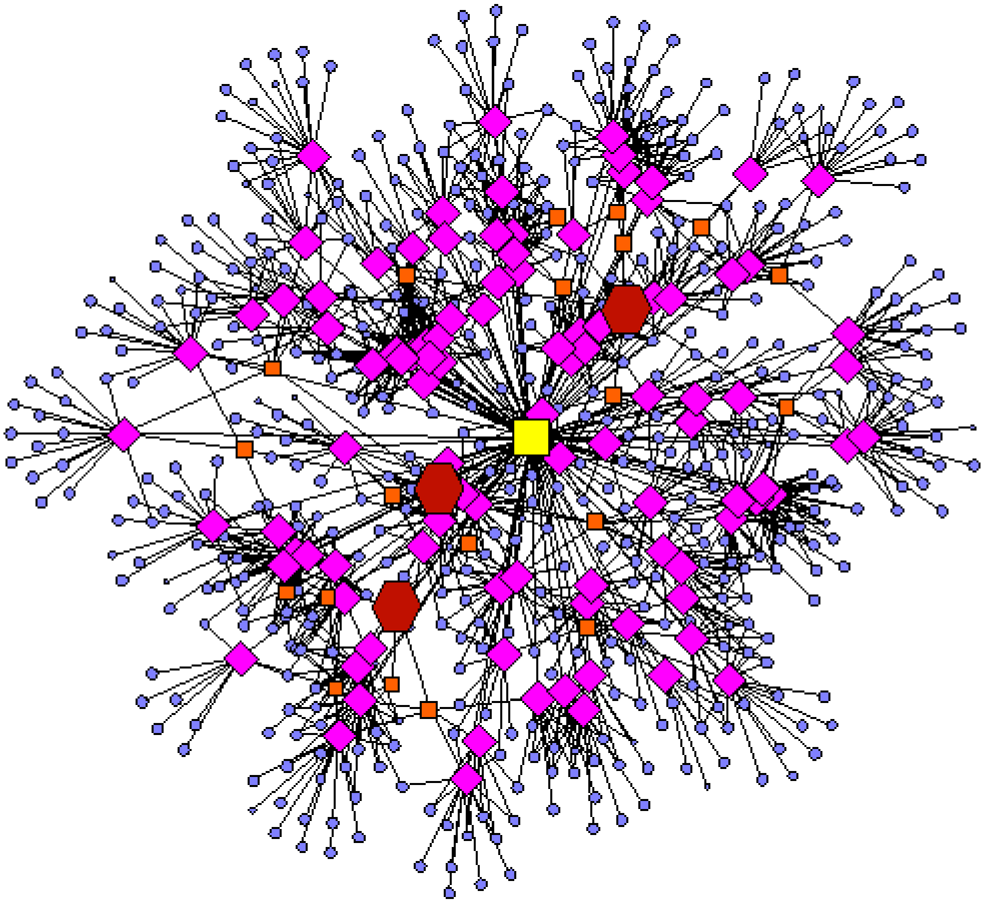


Figure 9. Diagram for the “abstract” network

The approach that we have used in Phase 1 to generate primary relationships for shipments between operations yields a network where some operations are better connected than others. For instance, **Figured 10** is a blowup diagram of the upper left hand corner of an abstract network. The feedlot shown has 13 stocker operations feeding it, and 65 cow-and-calf ranches feeding these stocker operations.

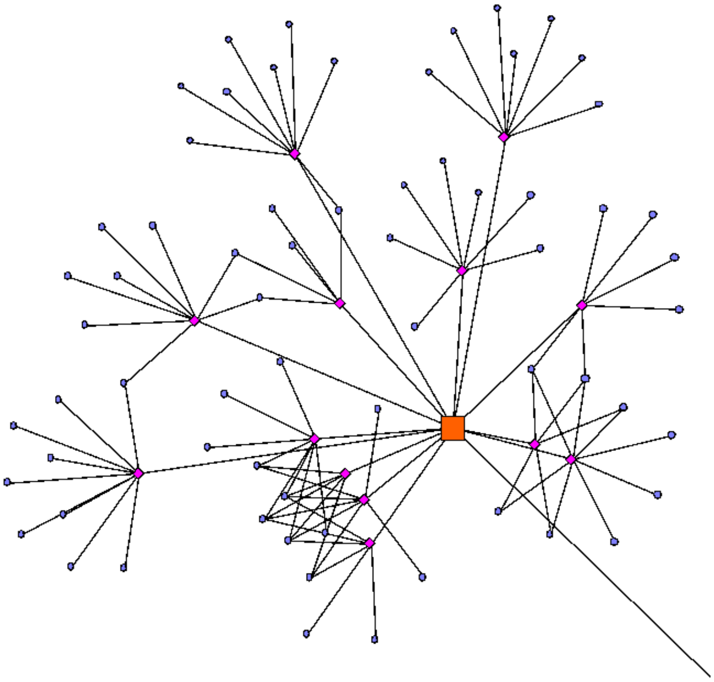


Figure 10. A blow-up diagram of the “abstract” network for a well-connected feedlot

At the end of the simulation, the network is re-drawn with the width of links to represent the total transfer of cattle along the primary connection. An example of a region near the left hand meat-packing plant is shown in **Figure 11**.

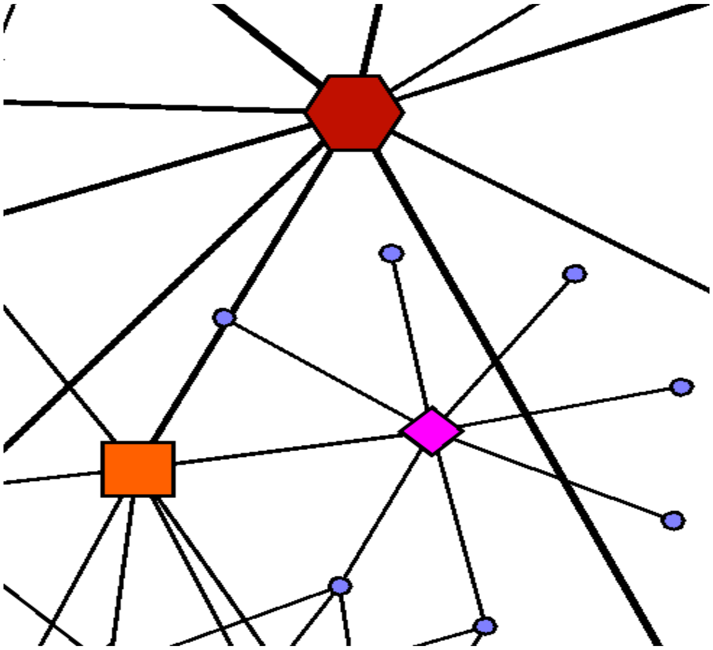


Figure 11. A blow-up diagram showing different width of links

6.2.2 Number of Cattle within operations in time

Figure 12 contains a plot of totals across operation types, and example plots for each operation type. Note the initial buildup of cattle within the cow-and-calf ranches and the drainage of cattle from stocker operations and feedlots (before day 1,000). After this initialization period, we reach a "level" number of cattle within the system in cow-and-calf ranches, and steady fluctuations in stocker and feedlot operations.

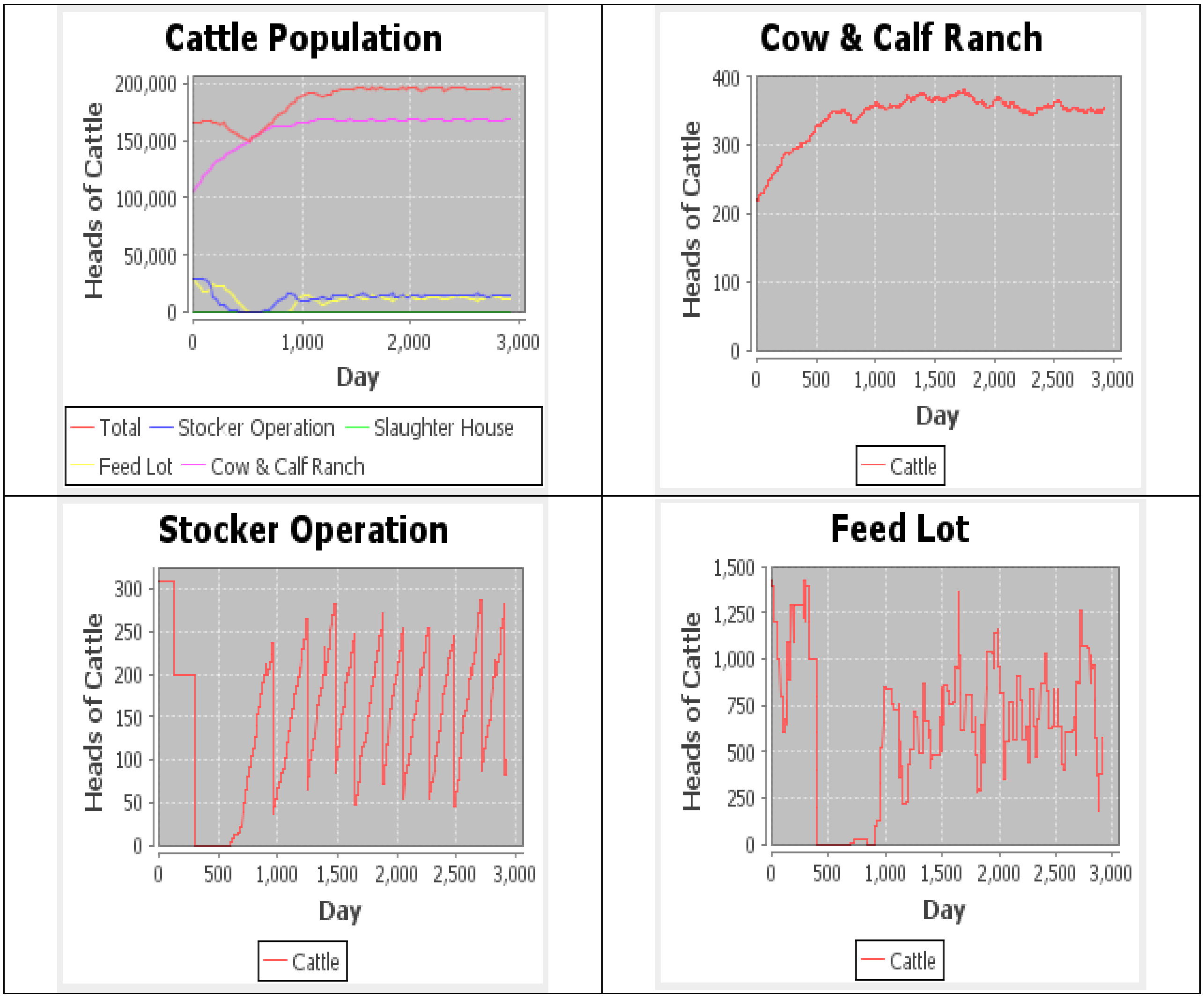

Cattle Population
Cow & Calf Ranch
Stocker Operation
Feed Lot

Figure 12. Cattle population plots

6.2.3 Cow-and-calf ranches

Figure 13 contains two typical cow-and-calf ranch plots, along with their link plots connecting them to stocker operations. Note that not all shipments go to the primary stocker operation. If this primary linked operation is at capacity, the stocker operation that is in greatest need within the entire system is selected to receive the calves.

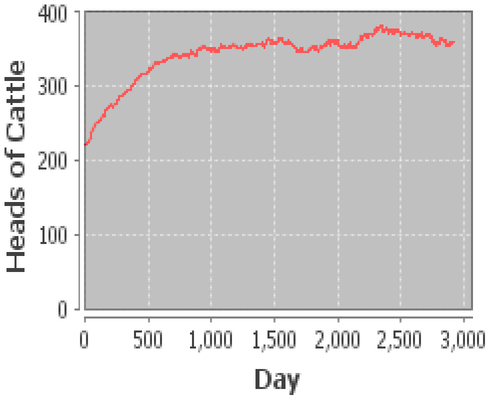
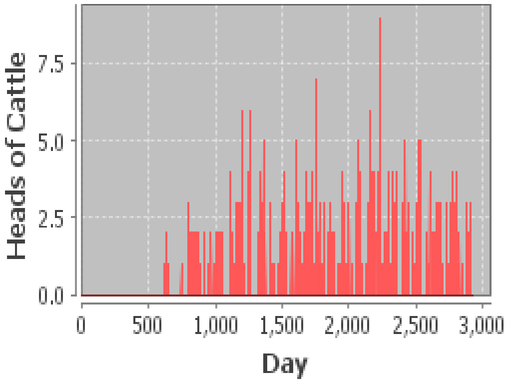
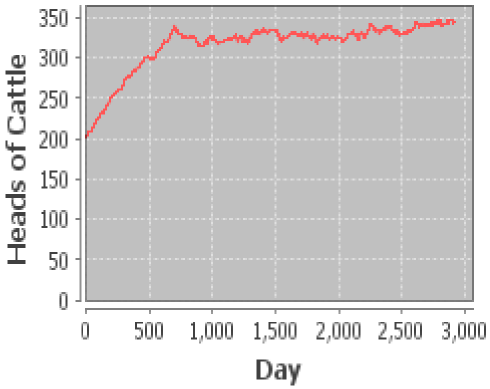
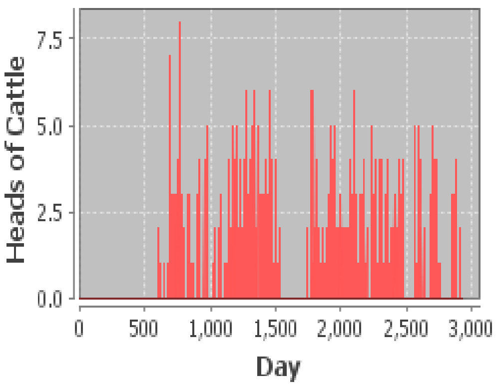
Number of Cattle in One Cow-and-Calf Ranch	**Shipments of Cattle from One Cow-and-Calf Ranch to One Stocker Operation**
	
	

Figure 13. Sample cow-and-calf ranch plots, and link plots denoting shipments to stocker operations

6.2.4 Stocker Operations

Figure 14 illustrates a stocker operation well-connected to upstream cow-and-calf operations, that tends to stay near its capacity (on the left), and a poorly-connected stocker operation, that tends to stay well below capacity (on the right).

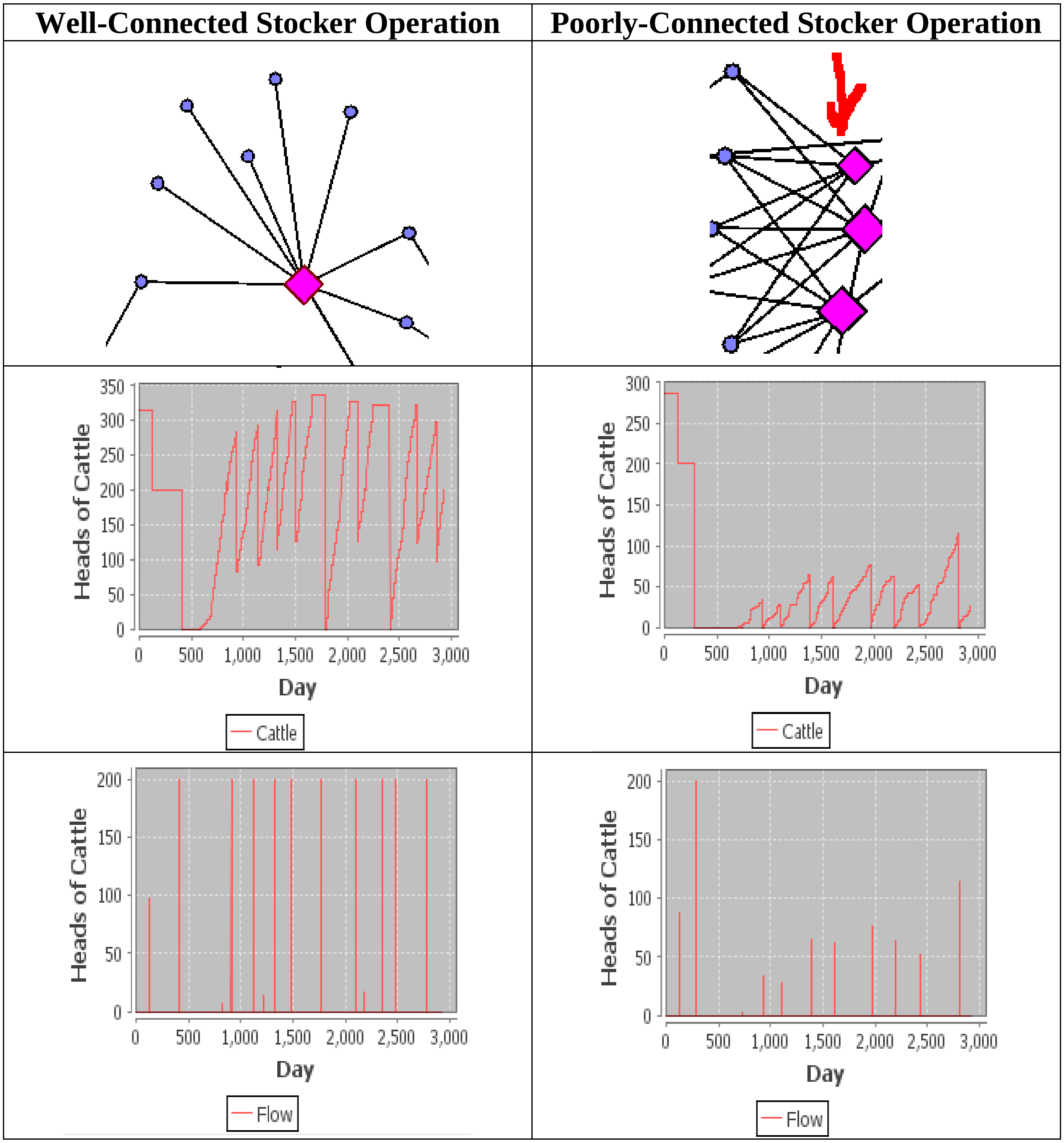


Figure 14. Sample stocker-operation plots, and link plots denoting shipments to feedlots

6.2.5 Feedlots

Figure 15 displays a well-connected feedlot operation, that tends to stay near its capacity, and a poorly-connected feedlot operation, that tends to be well below capacity.

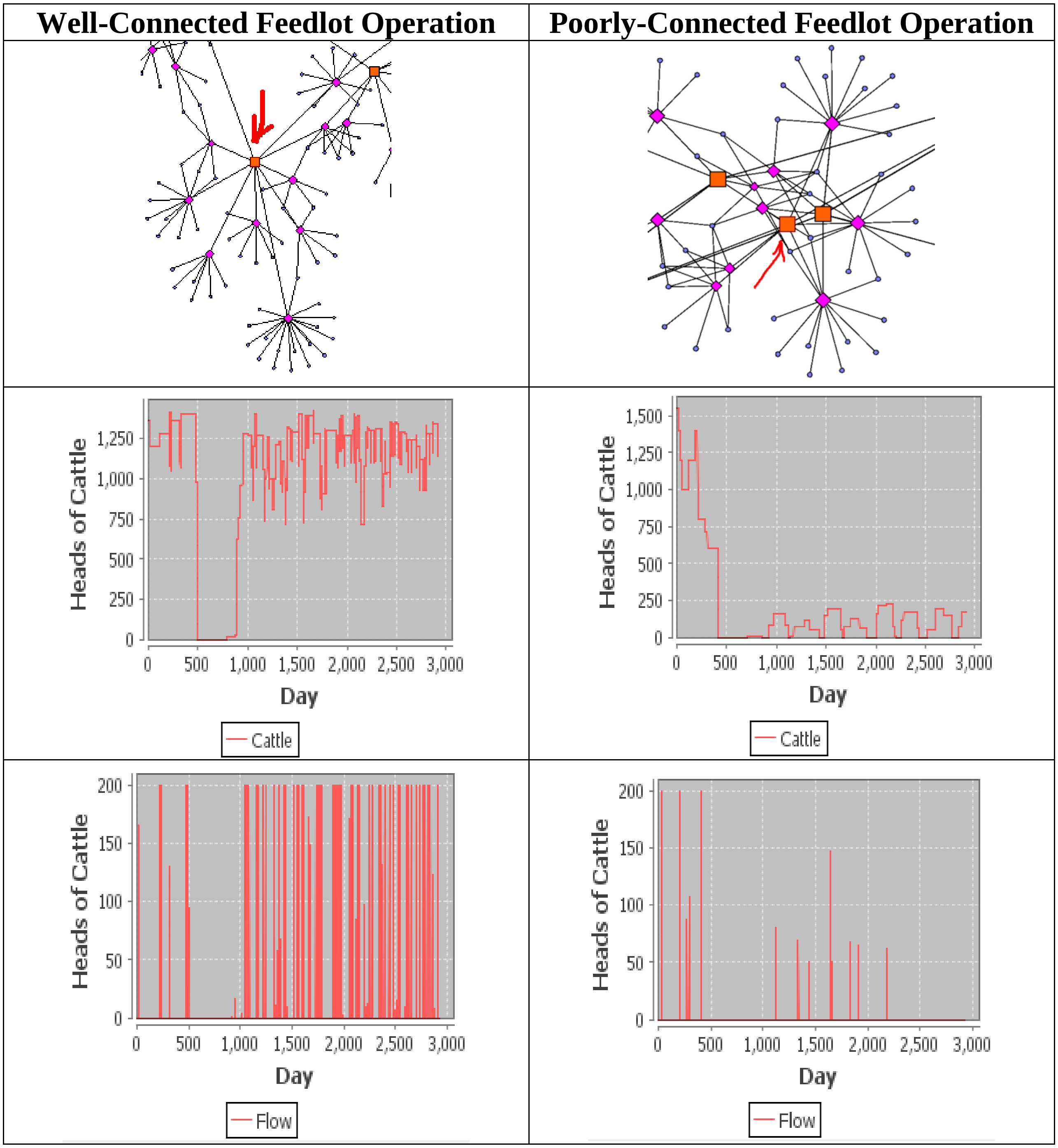


Figure 15. Sample feedlot plots, and link plots denoting shipments to meat-packing plants

6.2.6 Meat-Packing Plants

Figure 16 shows plots for the two meat-packing plants. They both behave similarly.

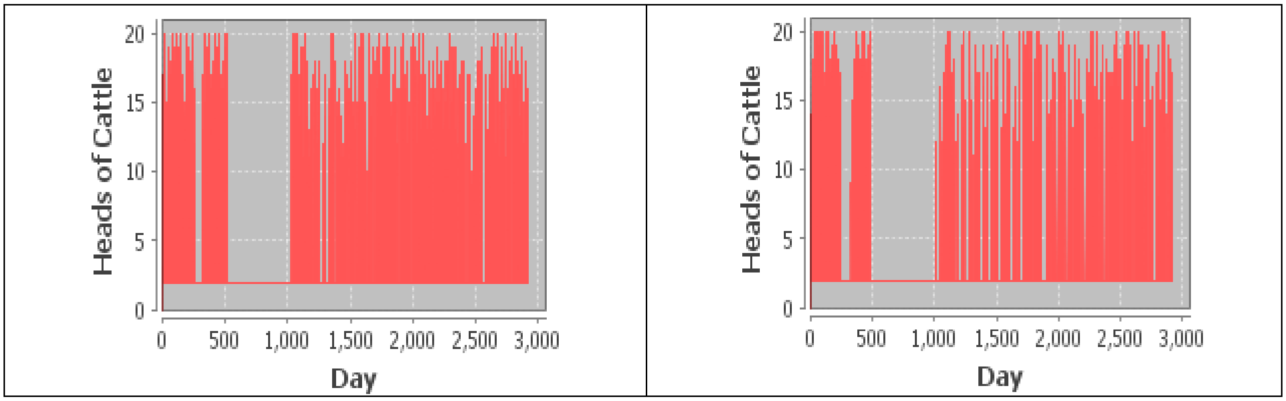


Figure 16. Meat-packing plots

6.2.7 Culled-Cow Shipments

Figure 17 contains a network plot showing culled-cow shipments (brown) and a plot for the circled shipment link.

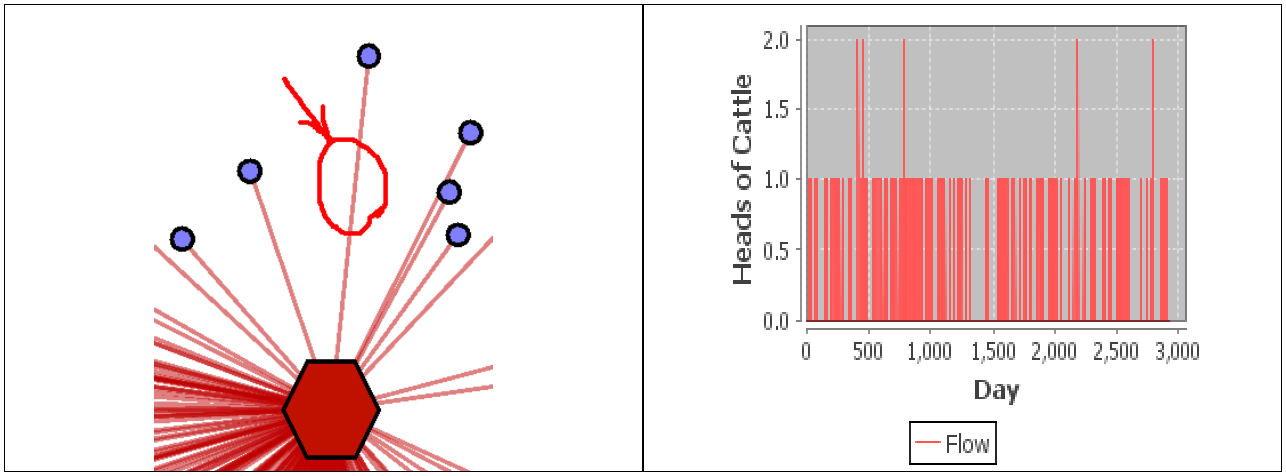


Figure 17. Network plot showing culled-cow shipments and a link plot denoting the shipments from one cow-and-calf operation to the meat-packing plant

6.2.8 Non-primary link shipments from cow-and-calf operations

In **Figure 18**, we show the calf shipments from cow-and-calf operations that are not along the primary link in red for a portion of the network. These operations are processed through a sales barn (the blue star.) Very few transfers take place along these links and only occur when the primary stocker operation is at capacity and cannot accept additional calves. These out of primary shipments radiate to the operation that is in most need (furthest below capacity).

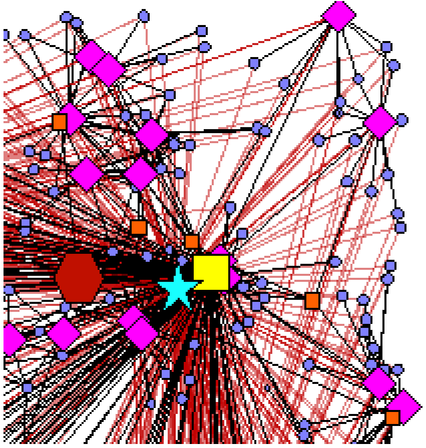


Figure 18. Diagram of Sales barn in Network including non-primary links (in red)

7 Future Directions and Development

Once we have assured that our Phase One model is working correctly we will begin to implement:

- Disease tracing analysis
- Mitigation policy analysis, particularly the comparison of political borders to cattle lifecycle networks and the effectiveness of policy application via each path
- Modify the model schema to apply analysis to other livestock diseases, such as Rift Valley Fever

8 References

Andersen DF and GP Richardson. 1997. Scripts for group model building. *System Dynamics Review* 13 (2): 107-129.

New Mexico Agricultural Statistics 2007. USDA. NASS. New Mexico Field Office (PO Box 1809, Las Cruces, NM, 88004)

Richardson GP and DF Andersen. 1995. Teamwork in group model building. *System Dynamics Review* 11 (2): 113-137.

Rouwette EAJA, JAM Vennix and T van Mullekom. 2002. Group model-building effectiveness: A review of assessment studies. *System Dynamics Review* 18 (1): 5-45.

Vennix JAM. 1996. *Group Model Building: Facilitating Team Learning Using System Dynamics*. London: John Wiley & Sons.

Vennix JMA, DF Andersen and GP Richardson (Eds.). 1997. Group Model Building. *System Dynamics Review* 13 (2): 103-106.

9 Appendix A: A System Dynamics Model of the Beef Aging/Supply Chain

A System Dynamics (SD) model provides an aggregate simulation for a beef cattle population, scaled to a) an arbitrary-size operation, b) animals from New Mexico, or c) the entire country. It concerns only with the aging and supply chain of beef cattle, and uses average parameter values for the entire population. It accounts for the beef cattle lifecycle, based on average lengths-of-stay in each life stage, but does not account for the economics of the industry.

Under stable industry conditions, this simulation is capable of replicating the actual flows and accumulations of animals, in aggregate, thus providing a means to validate the logic and parameters of structural assumptions embedded in the finer-grained Agent Based (AB) model. Also, where parameter values for the AB model are not readily available, they can be inferred from the simulation of the SD model.[14]

9.1 The Purpose of the SD Model

In summary, with this model we will be able to:

- Provide an aggregate conceptual and computational description for a beef cattle population
- Cross check parameter values where they are (or as they become) available
- Extract average parameter values where those are not readily available

This work informs the Agent Based (AB) model, which has a granular level of aggregation designed to capture individual operations and for tracking single animals.

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[14] The SD model was developed for another project, prior to this application, but it was simplified and refined, based upon the information obtained in the elicitation meeting on 10/28/2009, to help inform the development of the AB model.

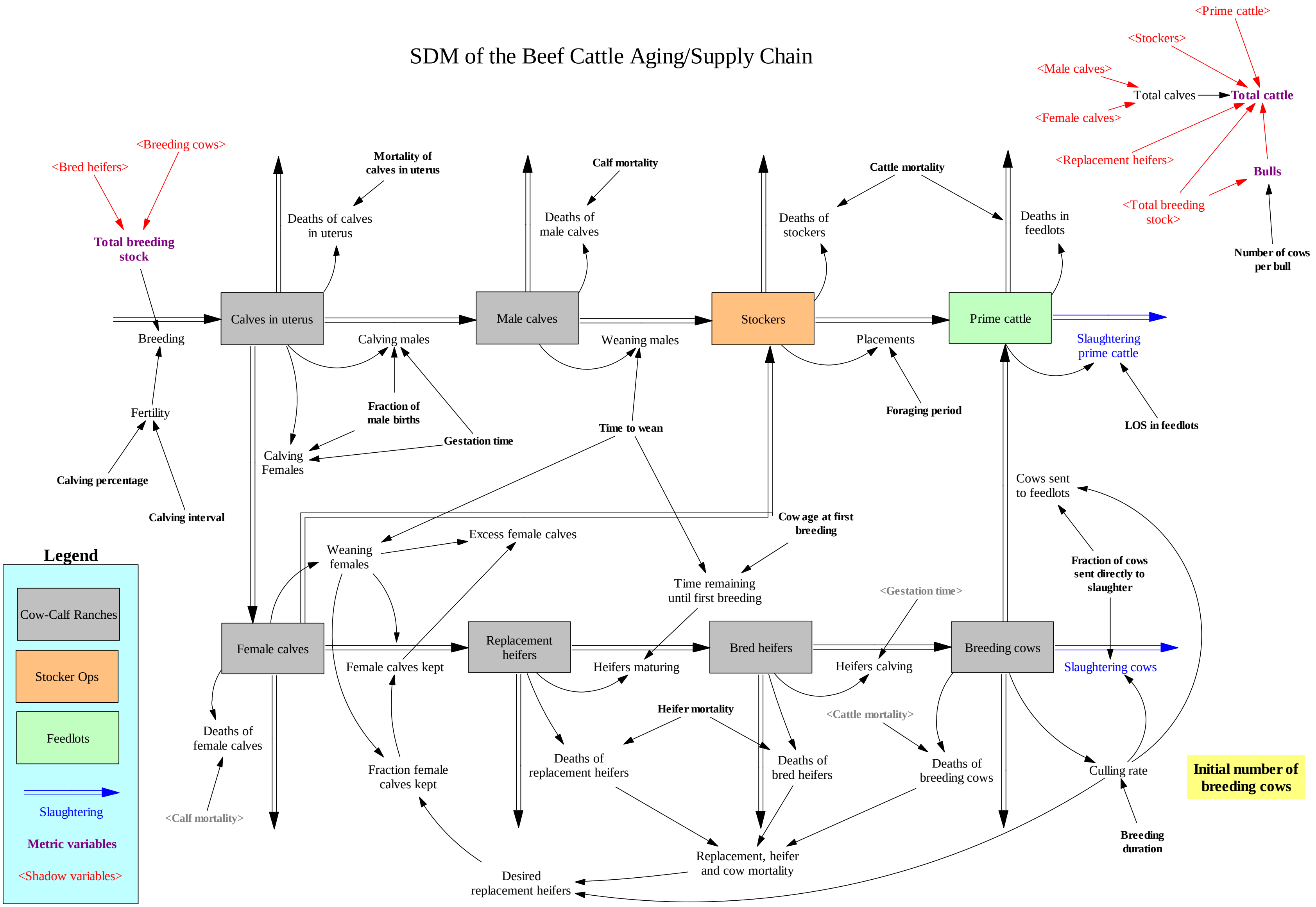

Figure 19: A System Dynamics model of the beef aging/supply chai

9.2 An overview

The description of the SD model follows the conceptual diagram provided in **Figure 19**.
The SD model captures two types of lifecycle in the aging/supply chain of beef cattle. The first is the normal lifecycle of the male animals, which lasts approximately eighteen months, from birth to slaughter. The second is the normal lifecycle of the female breeders, which lasts approximately ten years. Not all of the females follow the lifecycle of the breeders; approximately 60 percent of the females migrate to the path of the males after being weaned. A very small fraction of the males are raised as bulls for reproduction and experience a long life.

The normal lifecycle of the males is depicted in the top aging/supply chain, while the normal female breeder lifecycle is captured in the bottom aging/supply chain. The bulls are not accounted for directly due to their small population size and distinct lifecycle. Instead, they are computed as a fraction of the number of cows in the model. Eventually, all of the healthy animals are slaughtered, whether at young or old age. The remainder of this Appendix describes this aging/supply chain in detail, including average parameter values, equations, and the results of simulations for different scales of operation.

9.2.1 Calves in Uterus

Calves in uterus are a result of breeding mature heifers, and cows, annually. About 75 percent of the breeding stock (including heifers breeding for the first time) conceives:

Breeding = (Bred heifers + Breeding cows) * Calving percentage / Calving interval

The gestation period is of nine months, and about half of the births are male:

Calving males = (Calves in uterus / Gestation time) * Fraction of male births
Calving Females = (Calves in uterus / Gestation time) * (1 - Fraction of male births)

Calves in uterus accumulate during the gestation period according to the following formula:

Calves in uterus = INTEG (Breeding - Deaths of calves in uterus - Calving males - Calving Females)

9.2.2 Male Calves

Male calves are weaned in approximately six to eight months, when they weigh 500-600 pounds:

Weaning males = Male calves / Time to wean

Their accumulation is determined by this formula:

Male calves= INTEG (Calving males - Deaths of male calves - Weaning males)

9.2.3 Female calves

Female calves are weaned similarly to male calves. Only a fraction of the female calves are kept as replacement heifers. These animals will substitute breeding cows that are culled due to aging, as well as any other females dying in the breeding chain:

Weaning females = Female calves / Time to wean
Female calves kept = Weaning females * Fraction female calves kept
Fraction female calves kept = Desired replacement heifers / Weaning females
Desired replacement heifers = Replacement, heifer and cow mortality + Culling rate

After they are weaned, the excess female calves are sent to the stocker operations, similarly to their male counterparts:

Excess female calves = Weaning females - Female calves kept

Female calves accumulate during the weaning period according to the following formula:

Female calves= INTEG (Calving Females - Deaths of female calves - Excess female calves - Female calves kept)

9.2.4 Stockers

Once weaned, the male calves and the excess female calves are placed in stocker operations until they mature into steers and heifers, respectively, weighing from 750 to 900 pounds. The foraging period varies from four to twelve months, depending on what they are fed (wheat or grass).[15] Afterward, the animals are placed in feedlots:

Placements = Stockers / Foraging period

Stocker accumulation is determined by this formula:

Stockers= INTEG (Weaning males + Excess female calves - Deaths of stockers - Placements)

9.2.5 Replacement Heifers

Replacement heifers conceive their first calf at an age of approximately fifteen months:

Heifers maturing = Replacement heifers / (Cow age at first breeding - Time to wean)

Their accumulation is determined according to the following formula:

Replacement heifers= INTEG (Female calves kept - Deaths of replacement heifers - Heifers maturing)

9.2.6 Bred Heifers

Bred heifers calve following a nine-month gestation period:

---

[15] We assume this variation is mostly due to an attempt to adjust the timing so that the slaughtering operation is buffered from the seasonality associated with the births, which happen mostly in the spring of each year. For simplicity sake, we assumed weaning, foraging, and feedlots take six months each (18 months in total).

Heifers calving = Bred heifers / Gestation time

Bred heifers shift to breeding-cow status after successfully delivering their first calf. Therefore, their accumulation is determined by the formula:

Bred heifers = INTEG (Heifers maturing - Deaths of bred heifers - Heifers calving)

9.2.7 Breeding Cows

Cows are bred until eight to ten years of age. Since they are approximately two years old at first calving, this means they have a breeding duration of six to eight years, at which point they are culled:

Culling rate = Breeding cows / Breeding duration

The majority of the cows culled are sent directly to slaughter, while some are first sent to specialized feedlots:

Slaughtering cows = Culling rate * Fraction of cows sent directly to slaughter
Cows sent to feedlots = Culling rate * (1 - Fraction of cows sent directly to slaughter)

Therefore, breeding cows accumulate according to the following formula:

Breeding cows = INTEG (Heifers calving - Deaths of breeding cows - Cows sent to feedlots - Slaughtering cows)

9.2.8 Prime Cattle

Prime cattle are animals confined in feedlots, and fed a high concentration of corn and protein to maximize gains and feed efficiency. Typically, the animal will be marketed to a packing plant with a weight of 1,100 to 1,250 pounds.[16] Normally this process takes six months or less:

Slaughtering prime cattle = Prime cattle / LOS in feedlots

Thus, the accumulation of prime cattle is determined by this formula:

Prime cattle= INTEG (Placements + Cows sent to feedlots - Deaths in feedlots - Slaughtering prime cattle)

9.2.9 Mortality Rates

The mortality rates at each point of accumulation depend upon lifecycle death risks, which are lowest for stockers and prime cattle, and highest for calves in uterus:

Cattle mortality ~ 1.5 percent per year (for steers and prime cattle)
Calf mortality ~ 5.5 percent per year

---

[16] "Large frame steers and heifers would not be expected to produce choice carcasses until their live weight exceeds 1,250 and 1,100 pounds, respectively." (http://www.ag.ndsu.edu/pubs/ansci/beef/as1163-1.htm#Beef)

Heifer mortality ~ 3 percent per year (higher than cattle due to problems associated with first time breeding)
Mortality of calves in uterus ~ 7 percent per year (calves born dead and aborted pregnancies account for 5.5 percent, while breeding cow mortality accounts for an additional 1.5 percent)

The following formulas determine the deaths of animals per category:

Deaths of calves in uterus = Calves in uterus * Mortality of calves in uterus
Deaths of male calves = Male calves * Calf mortality
Deaths of female calves = Female calves * Calf mortality
Deaths of stockers = Stockers * Cattle mortality
Deaths of replacement heifers = Replacement heifers * Heifer mortality
Deaths of bred heifers = Bred heifers * Heifer mortality
Deaths of breeding cows = Breeding cows * Cattle mortality
Deaths in feedlots = Prime cattle * Cattle mortality

9.2.10 Bulls

Bulls are accounted for indirectly, as a function of the number of cows per bull (one bull to every twenty cows):

Bulls = (Bred heifers + Breeding cows) / Number of cows per bull

9.2.11 Other Variables

Total calves = Male calves + Female calves
Replacement, heifer and cow mortality = Deaths of replacement heifers + Deaths of bred heifers + Deaths of breeding cows
Total cattle = Total calves + Replacement heifers + Total breeding stock + Stockers + Prime cattle + Bulls

9.2.12 Constants and Parameters

Breeding duration = 108 months

Six to eight births per cow in total, however, the calving percentage is about 75 percent. This means that most cows skip one out of every four years. This parameter accounts for the subtraction of the first calving and, thus, should be interpreted as the "remaining" breeding duration, five to seven births per cow. Finally, the cows are not culled immediately after giving birth to their last calf, since they are needed to wean the calf. So, the remaining lifetime of a cow once it enters this stage is conceptually between 86-118 months [(Average number of births per cow - First calf) * Number of months in year / Calving percentage + Time to wean]. The value that we used to parameterize the remaining breeding duration is nine years (108 months), which returns a culling rate close to ten percent per year, or about one tenth of the number of breeding cows plus bred heifers.

Calf mortality = 0.0046 per month

Approximately 5.5 percent per year, according to information obtained at the Taylor Ranch.

Calving interval = 12 months

It is assumed constant because breeding normally occurs once per year. The beef calving percentage is the parameter that should be adjusted to determine the fertility rate.

Calving percentage = 0.75 (dimensionless)

About 75 percent of the breeding stock (including heifers breeding for the first time) conceives.

Cattle mortality = 0.0013 per month

One and a half percent per year for steers and prime cattle.

Cow age at first breeding = 15 months

Calves are normally born in the spring and will give birth for the first time two years hence. Thus, they will breed for the first time in the fall prior to their second birthday (24 minus 9).

Foraging period = 6 months

Four to twelve months depending on what they eat (wheat or grass), or when they weigh between 750 and 900 pounds.

Fraction of cows sent directly to slaughter = 0.8 (dimensionless)

Most old cows are sent directly to slaughter, while others are first placed in specialized feedlots.

Fraction of male births = 0.5 (dimensionless)

This is the average proportion of calf-births that produce males; assumed constant.

Gestation time = 9 months

This is the normal length of pregnancy period for cattle; assumed constant.

Heifer mortality = 0.0025 per month

Heifer mortality is probably higher than for cattle due to problems associated with first-time breeding. We used three percent per year but this value could be wrong.

Length of stay (LOS) in feedlots = 6 months

The length of stay in feedlots is normally between 150 and 180 days.

Mortality of calves in uterus = 0.0058 per month

We assumed mortality of calves in uterus to be about seven percent per year in total. Calves born dead and aborted pregnancies account for 5.5 percent per year, while breeding cow mortality accounts for an additional 1.5 percent per year.

Number of cows per bull = 20 (dimensionless)

In average, one bull will cover about twenty cows.

Time to wean = 6 months

Average time for a calf to become a stocker is six to eight months, when they weigh 500-600 pounds.

9.2.13 *Initial Values for "Stocks"*

The initial values for seven out of the eight points of accumulation (stocks) in this model were derived for analytical equilibrium, as a function of the initial value of the eighth stock and of the model parameters, according to the equations below:

Initial number of calves in uterus = Breeding / (Mortality of calves in uterus + 1/Gestation time)
Initial number of male calves = Calving males / (Calf mortality + 1/Time to wean)
Initial number of female calves = (Replacement heifers * (Heifer mortality + 1/ Time remaining until first breeding) + Calves in uterus * (1 - Fraction of male births) / Gestation time - Culling rate - ((Replacement heifers + Bred heifers) * Heifer mortality + Breeding cows * Cattle mortality)) / (Calf mortality + 1/Time to wean)
Initial number of stockers = (Male calves / Time to wean + Calves in uterus * Fraction of male births / Gestation time - Breeding cows / Breeding duration - Female calves * Calf mortality - ((Replacement heifers + Bred heifers) * Heifer mortality + Breeding cows * Cattle mortality)) / (Cattle mortality + 1 / Foraging period)
Initial number of replacement heifers = Bred heifers * Time remaining until first breeding * (Heifer mortality + 1/Gestation time)
Initial number of bred heifers = Breeding cows * Gestation time * (Cattle mortality + 1/Breeding duration)
Initial number of prime cattle = (Placements + Cows sent to feedlots) / (Cattle mortality + 1/LOS in feedlots)

This means that changes in the "initial number of breeding cows" automatically generate steady-state values for all other stocks in the model, resulting in an analytical equilibrium for the chosen scale of the operation. In the next section, we use the capability provided by the SD model to simulate the size of the stocks and flows scaled to different sizes of operations. These simulations help us:

- Cross check parameter values against available data
- Extract average parameter values where data is not readily available

9.3 Simulations

We simulated the SD model for three scales of operation:

1) A hypothetical case sized to ten thousand beef cows;
2) Animals from New Mexico, anchoring the model at an estimated 460,000 beef cows;[17]
3) The U.S. beef industry, with approximately 32.2 million beef cows.[18]

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[17] New Mexico's inventory of beef cows as of January 1, 2008 (NM Agricultural Statistics 2007, pp. 28-30).
[18] Beef cows in the United States as of January 1, 2009 (NASS, USDA, Catt-07/24/09).

9.3.1 How to Scale the Size of the Operation?

The "initial number of breeding cows" is the parameter that serves to scale the size of the operation. The value of 9,133 scales the operation to about 10,000 cows (including bred heifers); 420,079 scales the simulation to New Mexico's 460,000 cows; 29,405,530 scales the simulation to the U.S.'s 32.2 million cows.

For each case, we document the steady-state values for the stocks and flows.

Table 1: Simulated *number of animals* according to the SDM for three scales of operation:

Populations	**Scaled to 10,000 cows**	**Scaled to New Mexico**	**Scaled to the United States**
Calves in uterus	5,346 fetuses	245.9K fetuses	17.2M fetuses
Male calves	1,734 calves	79.8K calves	5.6M calves
Female calves	1,734 calves	79.8K calves	5.6M calves
Total calves	3,468 calves	159.5K calves	11.2M calves
Stockers	2,841 head	130.7K head	9.1M head
Prime cattle	2,920 head	134.3K head	9.4M head
Replacement heifers	887 heifers	40.8K heifers	2.9M heifers
Bred heifers	868 heifers	39.9K heifers	2.8M heifers
Breeding cows	9,133 cows	420.1K cows	29.4M cows
Total breeding stock	10,000 cows	460.0K cows	32.2M cows
Bulls	500 bulls	23.0K bulls	1.6M bulls
Total cattle	20,618 head	948.4K head	66.4M head

Table 2. Simulated *flow* of animals according to the SDM for three scales of operation:

Flow of animals	Scaled to 10,000 cows	Scaled to New Mexico	Scaled to the United States
Deaths in uterus	372 fetuses/year	17.1K fetuses/year	1.2M fetuses/year
Deaths of calves	191 calves/year	8.8K calves/year	0.6M calves/year
Deaths in stocker ops.	44 head/year	2.0K head/year	0.1M head/year
Deaths in feedlots	46 head/year	2.1K head/year	0.1M head/year
Deaths of heifers	53 heifers/year	2.4K heifers/year	0.2M heifers/year
Deaths of cows	142 cows/year	6.6K cows/year	0.5M cows/year
Total deaths (except fetuses)	476 cattle/year	22.0K cattle/year	1.5M cattle/year
Births	7,500 calves/year	345.0K calves/year	24.1M calves/year
Excess female calves	2,259 calves/year	103.9K calves/year	7.3M calves/year
First breeding (heifers calving)	1,157 first-borns/year	53.2K first-borns/year	3.7M first-borns/year
Inflow into stocker ops.	5,727 head/year	263.4K head/year	18.3M head/year
Stocker inflow into feedlots	5,683 head/year	261.4K head/year	17.9M head/year
Cows sent to feedlots	203 cows/year	9.3K cows/year	0.7M cows/year
Total inflow into feedlots	5,886 head/year	270.7K head/year	18.9M head/year
Slaughtering prime cattle	5,840 head/year	268.6K head/year	18.8M head/year
Slaughtering cows	812 cows/year	37.3K cows/year	2.6M cows/year
Total slaughter rate	6,652 head per year	306.0K head/year	21.4M head/year