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Food systems veterinary medicine

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Abstract
The objectives of this review are to suggest the use of the systems thinking framework to improve how veterinary medicine is applied to food production. It applies the eight essential skills of systems thinking to a few selected veterinary examples. Two of the skills determine how we approach or define a problem, and are (i) dynamic thinking (taking a longer term perspective) and (ii) the 30,000 foot view (expanding the boundary of analysis beyond the animal, farm, or even country). The other skills are (iii) system-as-cause, (iv) operational thinking, (v) closed-loop (feedback) thinking, (vi) non-linear thinking, (vii) scientific thinking and (viii) generic thinking. The challenge is to adopt and apply this systems framework to veterinary medicine and food production. The result will be a rigorous new approach to solving the complex food and health problems of the 21st century.

Introduction

For good or for ill, food production is undergoing consolidation and intensification. Today, one decision affecting a single animal or operation may have a global impact (e.g. international trade bans due to one tissue-residue violation, or large-scale disease outbreak). In 3 months, one egg producer can supply consumers a half billion potentially contaminated eggs (FDA, 2010). In a very short time a new disease agent, such as Porcine Circovirus 2 can infect most of the world's pigs (Firth *et al.*, 2009). The number of people producing, therefore controlling food, is decreasing, with less than 2% of the population involved in the US (CIA World Factbook, 2011). Therefore, producers and their consulting veterinarians have influence on a much larger scope of animals, food, consumers and environment than ever before. No matter where in the food supply chain a veterinarian is working, he/she must understand the implications of decisions throughout the food, environment and public health systems.

Given the increasing world population, its prosperity and food safety demands, our food system will enjoy increasingly complex challenges (FAO, 2009; Parker, 2011). However, to address these challenges, veterinarians cannot totally depend on the classic reductionist scientific approach. As scientists we are trained to analyze problems. Analysis involves taking apart the functioning whole (reduction), studying the parts, then mentally reassembling the parts to hopefully provide an understanding of the whole and how it functions (SystemsWiki, 2011a). This reductionist or analytical approach is how we address most complex problems; divide and clump. For example, universities, businesses, medical professions (orthopedics, dermatology and soft tissue), scientific disciplines (e.g. engineering, computer science and veterinary medicine) are divided according to the 'parts' they study, also known as disciplines. As a solution to the disintegrated silo approach, many leaders have promoted a multi-disciplinary, now called 'one-health' approach to medicine, public health and food safety (Schwabe, 1982; One Health Commission, 2009). Recently, many within veterinary medicine and the food system have voiced the need for a systems approach (Hurd, 1985; Hoblet, 2003; Bernado, 2006). However, the rigor of a scientific discipline needs to be applied to these visionary aspirations (Forrester, 1994).

I am convinced that veterinarians have a built-in understanding of the systems approach. We understand that an animal is not the sum of its parts. Studying an animal's parts is a post-mortem exercise; obviously, the function has been lost. The systems are not operating. However, this systems understanding may have been lost in the later years of medical/veterinary training.

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It is possible that not since physiology class has the veterinarian or physician studied the operational attributes of the entire patient system.

A new mindset and rigorous problem-solving discipline is needed. As Einstein said, 'we cannot solve problems using the same thinking we used when we created them' (ThinkExist, 2010). Needed is a common language for discussing problems, alternative solutions and the potential consequences of proposed actions. Systems engineering/dynamics provides the disciplinary rigor for a functional problem-solving methodology. The systems approach is a holistic view of the elements and processes working together to produce a desired result or change an undesired system output. Systems engineering can help us understand the various interacting systems such as infectious agent, environment, animal hosts and food harvesting (Richmond, 2004; SystemsWiki, 2011b). Systems engineering has a methodology and standards of practice (Forrester, 1968; INCOSE, 2009).

'Thinking' is all about making mental models and evaluating alternative problem-solving approaches. We need mental models to make sense of the world and choose the action giving the highest probability of success. For example, we imagine what the traffic might be like on the highway route to work versus the back roads. We may imagine sitting in traffic or sailing down a country lane. We have a mental model, representing the bare essentials. We mentally simulate it to explore various outcomes then make a choice (management decision).

However, our personal or group mental models are inadequate to understand and address the complex, ambiguous and adaptive challenges we now face.

> 'The systems dynamics paradigm ... recognizes all systems as having the same fundamental structure of levels and rates (accumulations and flows) structured into feedback loops that cause all changes through time.'
>
> (Forrester, 1994)

In an April 2011 Systems Thinking conference held at Iowa State University, Chris Soderquist (http://www.pontifexconsulting.com) stated that systems thinking improves our capacity to develop useful mental models through its:

- Paradigm (systems thinking skill set)
- Language (stocks and flows)
- Process (collaborative scientific inquiry)
- Technology (simulation)

The challenge for us now is to adopt and apply these system standards to veterinary medicine and food production. The result will be a rigorous new approach to solving the complex food and health problems of the 21st century. The following discussion will demonstrate how systems thinking skills may be applied to food animal veterinary medicine. However, it should be obvious that the systems thinking skill set can apply to a wide range of problem-solving endeavors. The context and examples in this paper should be considered by anyone tasked with safely feeding a growing world population. Therefore, I will generally refer to the problem solver in these scenarios as the food-systems practitioner. It can apply to veterinarians or other agriculturalists, dieticians, in-plant quality assurance officers, or CEOs. Note, just because someone is working within the food system does not mean one is applying the systems approach.

Conversational systems thinking skills

Overview

The 'systems approach' has been largely developed for engineering applications (INCOSE, 2009). However, as early as 1954, Ludwig von Bertalanffy (Bertalanffy, 1968) recognized the framework as an important perspective for all types of problem solving. Forrester (1994) and others (Senge and Sterman, 1990) recognized the value of this skill set for many other societal problems.

Currently, one of our main challenges to application in the food system is translation from engineering to food production. The work of Barry Richmond and others has done a great deal to move this framework into other areas including the teaching of science in high school (Draper, 2010). Therefore, the eight systems thinking skills described by Richmond will serve as the foundation for this paper's translation to veterinary medicine and the food system. The eight skills with my short hand translational test questions are as follows:

1. The 30,000 foot view – what are important external forces or inputs affecting the problem?
2. System-as-cause – what structural relationships are involved?
3. Operational thinking – how is this thing supposed to work? What are the cause and effect relationships?
4. Closed loop (feedback) thinking – what internal factors drive or impact the input and output relationships?
5. Dynamic thinking – what changes have or will happen as these processes continue?
6. Non-linear thinking – how will strength of input/output relationships change over time?
7. Scientific thinking – how can we build confidence versus prove the 'truth' or make predictions?
8. Generic thinking – How is this structure and functionality similar to other systems or experiences?

In this paper, I will offer some food animal examples of how these skills might be applied. The examples will not be detailed. Some may be suboptimal, but they will hopefully get us started down the path of learning.

The 30,000 ft view

Taking the 30,000 ft (10,000 m) view is likely one skill at which most food-systems practitioners are fairly adept.

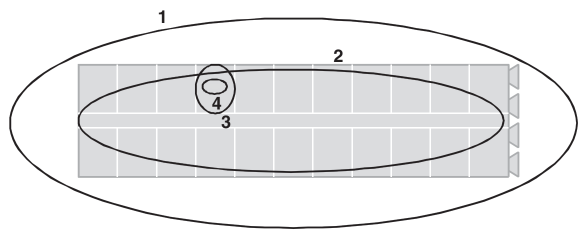

Fig. 1. Four circles of pig health evaluation.

When called to treat a sick animal, the experienced practitioner usually thinks about nutrition, housing, environment and a wide range of relevant factors. He/she must also take into consideration the inputs being used in production, such as young stock and feed ingredients. For example, dried distillers grains have become an important part of many rations, presenting new quality control, storage and feed delivery challenges. Many practitioners are familiar with 'corn-pickers or haymakers disease', an odd collection of maladies occurring around harvest time likely due to changes in management's attention to routine duties. However, in an effort to quickly treat the problem and move on, the food-systems practitioner may dive into depth before sufficiently exploring the problem to the edge of its possible boundaries. Some effort and discipline at moving from the presenting problem to a study of the 'big picture' may result in better solutions for the client.

It is important for the food-systems practitioner to develop the mental discipline of thinking horizontally. Related to this exercise is the decision to set a boundary to the problem that will be addressed. Every system exists within a system, which exists within a system, and so on. Therefore, the practitioner must decide, 'for today's exercise or thought experiment, or to treat today's problem, we will stop here'. The quote by Deming, that 'all models are wrong, some are useful' derives part of its truth from boundary setting (Richmond, 2004). Because not every problem can be solved today, the circle of influence must be clearly described. The circle of influence is defined as things that can be impacted, whereas the circle of concern includes things that people may worry about, but cannot necessarily change (Covey, 1989). Haimes (2004) describes an interesting corollary between the systems approach and Covey's Seven Habits.

As an example of the 30,000 ft view, Dr A. Ramirez (Iowa State University) has developed the Four Circle Approach to Pig Health (Fig. 1). In this approach the investigator completes four mental or physical examinations of the system:

1- on the outside of the building/site
2- on the inside of the building
3- in an individual pen
4- in an individual animal

System-as-cause – what structural relationships are involved?

The skill of thinking 'system as cause' can be exercised by asking the question, 'What are the structural relationships involved in the problem being presented?' Or, 'how is the system responsible for the behavior?' 'Mental models should contain only those elements whose interaction is capable of self-generating the phenomenon of interest' (Chris Soderquist, personal communication, 2010).

Again, the experienced veterinarian understands there is a big difference between signalment (presenting symptoms) in an individual animal, and the diagnosis. 'He is lame doc' is not a diagnosis. A careful examination, with some data from diagnostic testing, will likely reveal the structural anatomical problem; system as cause. This same perspective is needed with analyzing the presentation of a problem within a food production system. For example, the problem, 'we are not weaning enough pigs' may be due to piglet death from disease, sow milk production or failure to breed enough sows 4 months earlier. Another structural example might be insufficient number of bulls in the field with open cows at the correct time. Yet another example might be a large number of animals with skin lesions. Isolation of bacteria from those lesions might suggest a causative agent and a course of treatment. But antibiotics are not a systems solution. Focusing on a disease agent may not provide a sustainable solution. This increase in lesions might actually be due to a change in animal grouping and social structure that has upset the animal hierarchy, a problem antibiotics will not cure.

A way to discover system-as-cause phenomenon in medicine is to ask, 'Would we have the same or similar problem even if a different infectious agent were involved?' Neonatal diarrhea or 'failure to thrive' is often a systematic problem that we may loosely call 'bad management'. The infectious agent isolated varies because something else in the system is really causing the problem.

For example, by using a systems approach, the transportation and lairage system was identified as a 'cause' for increased *Salmonella* prevalence in pork production (Hurd *et al.*, 2001c, 2002). For these studies, the 'flow' of *Salmonella* positive pigs was measured before and after the loading, shipping, holding (lairage) and slaughter processes (Dickson *et al.*, 2003). To confirm our mental model the physiological feasibility of rapid *Salmonella* infection was then evaluated using a reductionist approach (Hurd *et al.*, 2001a, b). Taking an approach that measured the dynamic behavior of *Salmonella* in pigs and processing allowed the identification of lairage as an underappreciated but significant *Salmonella* source. Had we retained our previous mental models about *Salmonella* transmitting from infectious to susceptible animal, the role of environmental (lairage) exposure may have been overlooked.

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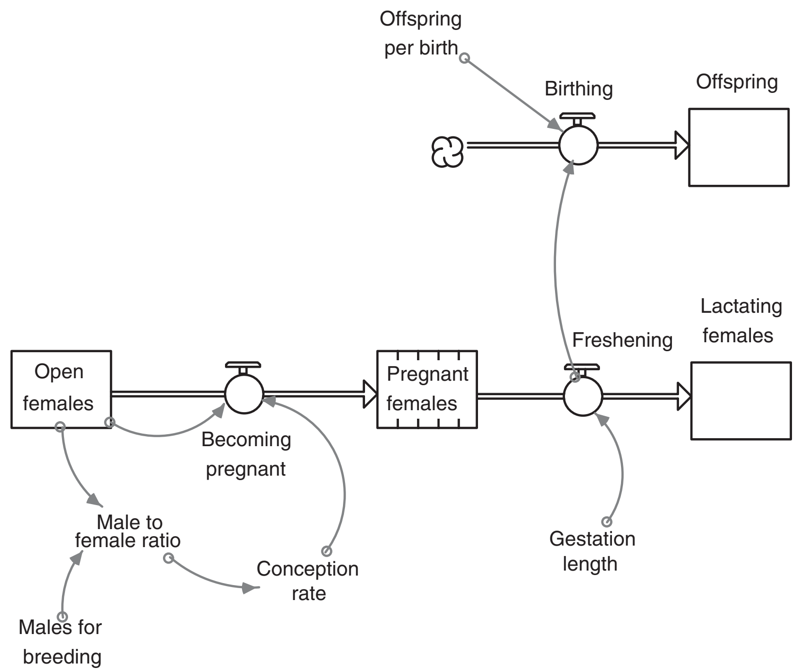

Fig. 2. STELLA® map of the generic 'breeding system'. Two outputs of interest are shown, lactating females and offspring.

Dynamic thinking

Attempting to simulate, mentally or *in silico*, behavior patterns leads the food-systems practitioner into the next systems thinking skill, dynamic thinking. A system is not static. Whether it is an animal, a farm, a packing plant, a supply chain or a business, a system is a living organism full of change and surprise. However, as a practitioner attempting to fix a problem, we often attempt to 'freeze' the system in time, so as to dissect it; focusing on the event. This attempt at 'freezing' is inherent in common epidemiologic tools, such as the prevalence rate or the cross-sectional study, or the practitioner's first question on the farm: 'what is the problem today?'

Understandably, it is very difficult to diagnose and repair a moving vehicle. However, dynamic thinking considers the event in the context of 'how you got there' and 'how you'll get to where you want to go'. It is best to look for trends/patterns of behavior shifting from the 'event focus'. It is generative–you can focus on the issue/problem as well as the underlying processes that have moved the system to its current condition.

If the food-systems practitioner is attempting to solve a problem in the system, then prospective longitudinal data are required. The experienced herd-health practitioner will likely be in a professional relationship that involves frequent review of records, analyzing for positive or negative trends in key parameters, monitoring the impact of changes. Some practitioners may even be using Statistical Process Control to see if trends are outside the expected range due to randomness in the system or some other systemic change (Wheeler, 1993).

Dynamic thinking might also add the consideration of other changing inputs into the system to see if they are affecting the trend lines. For example, does changing moisture or nutrient content of a key feed ingredient help explain the dynamic behavior? Is there an extraneous build-up and threshold process that might be driving the problem? For example, does the build-up of *Listeria* contamination in a meat slicer explain the periodic regulatory violations? Does the dynamic impact of seasonal breeding result in excessive stocking density factor (SDF) during certain seasons? For example, there may be an overlap between the models shown in Figs. 2 and 3. If the disease process in Fig. 3 is occurring within the population of pregnant animals in Fig. 2, then SDF may increase during certain times of the year, driving the infection process faster, creating an epidemic.

Dynamic thinking also 'thinks' forward. What might the trend in the future look like without intervention? What would we ideally like the trend to look like? If we intervene with Intervention X, what is the likely trend? How does my prediction of likely trend differ from others, and why?

Operational thinking

For the individual animal, the discipline of operational thinking is inherent to veterinary medicine. If the respiratory system is not working (operating) we expect a set of predictable system behaviors and symptoms. The challenge is that some of those symptoms may occur when other systems malfunction. For example, an examination of a coughing dog may start with the respiratory system, but should soon progress to the circulatory system which may not be operating correctly, allowing fluid build-up in the lungs.

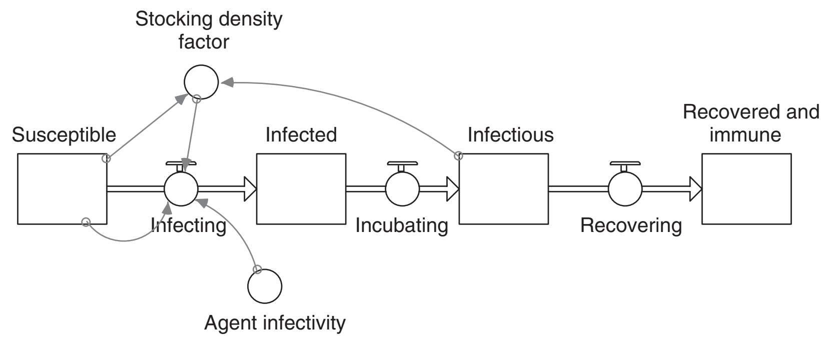

Fig. 3. STELLA® map of the infectious disease process showing the 'states' through which an animal may transit during the course of an epidemic.

The challenge for the food-systems practitioner is to apply this same problem-solving framework to larger food system and/or farm questions. Operational thinking suggests we focus on functionality. What are the cause-and-effect relationships that are producing the behaviors (desirable or non-desirable) being observed? The practitioner should ask, 'what is this system meant to do, how well is it doing it, why or why not?' For example, the breeding system may be meant to produce lactating cows for milk sale; or to produce specialized purebred genetic stock, or hybrid animals to be raised for meat. The function or operation of the system will affect decisions about care and management.

However, the practitioner is often anxious to fix (treat) the problem and move on. Therefore, a valuable tool for the practitioner has become the differential diagnosis list (Cornell University College of Veterinary Medicine, 2011). Based on the presenting signs, experiential familiarity with the system, and some medical training, the practitioner develops a list of possible 'causes' for the presenting problem then proceeds with diagnostics that may eliminate the unlikely 'causes'. Unfortunately, the differential diagnosis list does not overtly address interactive functionality of systems (Richmond, 2004).

Long term, effective and sustainable (lasting) solutions are more likely if we build a full and rich description of the system as it currently exists and make corrections accordingly. One useful method is to draw out (model) the inputs, and outputs of interest, connecting them with the processes that convert those inputs to outputs. These outputs could include desirables such as meat and milk, and non-desirables, such as human cases of salmonellosis. Fig. 2 shows such a model for the generic breeding system.

This figure demonstrates the commonly used key elements needed to describe a system using the nomenclature of a convenient software tool called STELLA (ISEE Systems, 2011). These elements are: (i) inputs and outputs (flows represented by a large arrow with 'control valve'), (ii) stocks or state variables (rectangles) and (iii) converters (circles with connecting arrows). Stocks are measurable units at some point in time. They may be the number of lactating cows, the number of infected sows, the number of bales of hay, etc. The flows between stocks can be thought of as processes that transform something into something else. For example, the birthing process transforms a pregnant animal into a lactating animal and also generates offspring. The breeding process transforms an open animal into a pregnant one. As stated, the number of individual units before or after a transformation process is shown in the square boxes called 'stocks' or state variables.

Transformation is common in the food system. In fact, transformation is the overarching operational goal of the food system; to convert feed, water, animals into safe and nutritious human food. Examples of food system transformations include:

- Susceptible individuals to infectious individuals
- Infected individuals to immune individuals
- Sick individuals to dead individuals
- Feed to body weight
- Live animals to carcasses
- Carcasses to meat (whole cuts, trim, ground)
- Food borne pathogens in meat to human illness
- Open animals to pregnant ones
- Milking females to dry (non-milking) females
- Unvaccinated to vaccinated animals
- Nursing to weaned offspring
- Sick to recovered animals
- Uncontaminated to contaminated product (e.g. food borne pathogen on a carcass)
- Tested for infection to known infected animal

When describing disease processes, rates of transformation can be recognized in epidemiologic terms such as incidence rate and case fatality rate.

Also, shown in Fig. 2 are circles called 'converters', which describe in more detail the relationships which affect the transformation process. For example, the ratio of males to females in a natural breeding system greatly impacts the breeding success (rate of transition from open to pregnant animals). As another example, we know that not every vaccinated animal will be protected. If we estimate the vaccine efficacy rate is 90% a converter

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would be used to convey how well the process works at transforming disease susceptible animals into immune and protected. If a process' goal is to test and remove infected animals from a population, then a converter (test sensitivity) can be used to describe the success at transforming suspect animals into known infected animals.

One can also see in Fig. 2 another element of systems thinking, namely, the boundary. For example, Fig. 2 and this printed page have a finite limit. Flows or stocks not shown here are assumed to be outside the boundary of concern for the moment. For example, animals that leave the farm to market are usually not the veterinary practitioner's concern, unless they are found to have an unacceptable residue of a drug the practitioner administered. Additionally, if that residue was found in product exported to a foreign country, the boundary or scope of the problem could grow to international proportions.

Unfortunately, boundary definitions often come prepacked in the form of our discipline, expertise or job description. A practitioner may be less likely to think of feed quality problems as he/she is not a nutritionist. The in-plant carcass quality control person may be less likely to think of on-farm structural changes as the reason for increased hide (skin) lesions. Some may have forgotten that hide was once skin, that a 'pluck' is the respiratory and cardiovascular system; that environmental (ventilation) problems may be the 'cause' of increased pluck adhesions. Most importantly, these evisceration quality issues may be increasing human illness such as salmonellosis (Hurd *et al.*, 2008b, 2011).

Feedback-loop thinking

Feedback-loop thinking is about 'connecting the dots' or clarifying the relationships that impact the rates of flow. For example, in our simple-breeding diagram (Fig. 2), the number of open females at any point in time will affect the rate of flow or movement (breeding) into the next state (pregnant females). Other variables also affect breeding, such as conception rate which may be affected by season and male-to-female ratio.

Fig. 3 shows a systems model for the spread of infectious disease. Here the number of susceptible individuals, the infectivity of the agent, and the SDF will impact the rate of conversion from susceptible to infected. Based on the latency of the disease, infected animals will also become infectious providing a reinforcing feedback loop to the infection flow, speeding up the course of the epidemic, up to a point. The feedback loop from susceptible to infecting is a balancing loop. As the number of susceptible dwindles, they are less likely to become infected and will slow down the rate of infecting. So this example demonstrates the two types of feedback loops that occur in systems: reinforcing (accelerate change) and balancing (push back against change). This model (Fig. 3) is a variation on the classic Reed-Frost model of infectious disease (LeFèvre and Picard, 2005). What is interesting about these models is how they can be used to 'predict' the behavior of an epidemic over time (dynamic thinking). As noted, feedback-loop thinking strives to discover and define the key internal relationships (information or resources) that impact the behavior of the system. The two examples above describe reinforcing or balancing loops.

Feedback loops can also be counteracting/balancing/draining. They serve to slow down or limit the process. For example, bacteria in fresh media will produce exponential growth (reinforcing loop) until other factors or constraints eventually limit long-term exponential growth. The food and space (resources) needs will eventually decline, limiting growth and possibly extinguishing the population (balancing loop). Additionally, infectious animals that move into the 'Recovered and Immune' state can no longer drive the infectious process. The number of susceptible individuals will eventually be depleted and the epidemic will subside, regardless of whether a veterinarian intervened or not.

At the end of a closed-loop thinking exercise, if there really can be an end, the practitioner should ask,

> 'Can the set of *reciprocal* relationships that I've pieced together in fact generate the behavior patterns that are being produced by the actual system?'
>
> (Richmond, 1991)

As with all modeling efforts, the power of feedback-loop thinking is not to 'predict' the future, but to gain insight for managing the system and correcting problems. For example, the breeding model (Fig. 2) could be used to adjust male-to-female ratios as the season progresses. Or the infectious disease model (Fig. 3) could be used to estimate the threshold proportion of resistant (herd immunity) animals required to avoid a major epidemic.

Non-linear thinking

Most veterinarians understand the meaning of a linear relationship; each causal factor impacts the effect by a fixed, proportional magnitude. For example, an $x\%$ increase in matings results in $y\%$ increase in calvings. However, for a non-linear relationship, 'the strength of the relationship will change with the magnitude of a third variable' (Richmond, 2004).

An easily recognized example of a non-linear relationship is that of drug dosing. For antibiotics, there is virtually no effect for a dosage below that which creates a minimum inhibitory concentration (MIC) in the target tissue (Andrews, 2001). Additionally, at doses above the MIC there is little improvement in performance. For other non-antibiotic drugs, the axiom, 'if a little is good, more is not always better' demonstrates the non-linearity principle.

Another example of a non-linear relationship might be the parameter 'conception rate' shown in Fig. 2. In a natural breeding situation, this rate is obviously affected by the bull to cow ratio. The acceptable ratio might be 1 : 25 (Sprott *et al.*, 2005). However, this optimal ratio may change as season and especially outdoor temperature affects bull activity, cow demonstration of estrus and survival of the newly fertilized embryo.

In the infectious disease example shown in Fig. 3, the impact of SDF likely changes in a non-linear fashion. This phenomenon is also recognized in our understanding of herd immunity (Peterson *et al*., 2007). It is accepted that 100% of a herd does not need to be vaccinated to prevent an infectious-disease outbreak. The reason is the non-linear relationship between the SDF and the infection process (Fig. 3). As the number of susceptibles decreases below a certain threshold, due to infection or vaccination, the impact of SDF becomes near zero and the infection process ceases. The SDF has decreased to the point that it is difficult to find an individual that is susceptible to infection. The behavior of this system over time should be predictable as described by the classic epidemic curve; where the number of infected increases exponentially up to the point where it reaches a plateau. The curve will have an S-shape.

If more non-linear relationships are included in the model, oscillations may occur such as the classic 'hog-cycle' (Meadows, 1970). As pig prices increase, the number of sows bred increases, after a delay of breeding and gestation time and finishing during which too many sows are bred; the market becomes 'flooded' with market pigs, sending prices back down (Stearns and Petry, 1996).

Scientific thinking

The meaning of scientific thinking in the context of food systems decision making is best described as 'show me the data'. According to Richmond (1993) it 'has to do with quantification more than measurement . . ., being rigorous about testing hypotheses . . .', not about predicting the future. As mentioned above, most thinking involves some sort of mental model that we 'simulate' or in which we role play. Scientific thinking means applying rigorous testing as we compare the outcomes of scenario A versus scenario B. Each thought experiment or simulation should be evaluated '. . . recording results–just as a scientist would do when conducting careful experiments in a lab' (Richmond, 2004). Scientific thinking is also about building confidence that the assumptions about how the system works are plausible and useful for the purposes of addressing an issue. We use computer and mental simulation to trace out the logical implications of assumptions and ask: does this help me understand the behavior? Does it help me know how to intervene? If not, we modify/add assumptions until the model can answer those questions. It is an iterative, hypothesis testing approach (Chris Soderquist, personal communication, 2011).

As an example, my experience analyzing the Danish pork *Salmonella*-control program may be instructive (Hurd *et al*., 2008a). The objective of this study was to build a model to conduct a dynamic (10 year) retrospective and prospective analysis of policies reducing human *Salmonella* risk. The details of the study will not be discussed here, but some results will be reviewed to

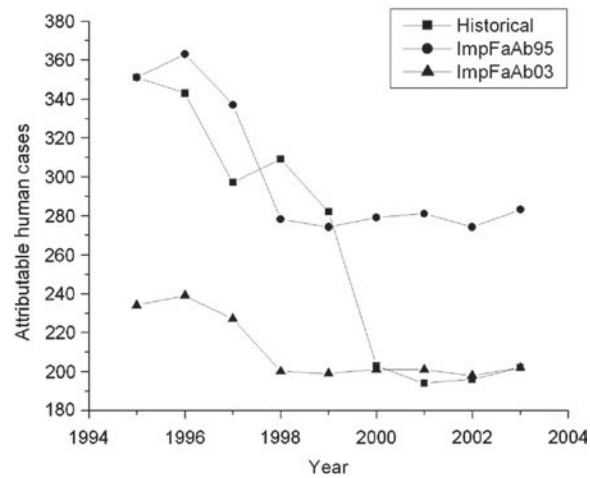

Fig. 4. Comparison of simulated total annual number of pork attributable human cases if on-farm control methods were used with 1995 (ImpFaAb95) or 2003 (ImpFaAb03) slaughter quality parameters.

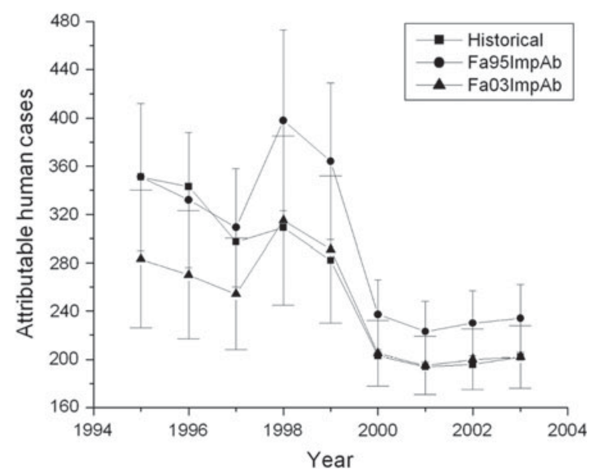

Fig. 5. Comparison of simulated total annual number of attributable human cases if abattoir method improvements were used with 1995 (Fa95ImpAb) or 2003 (Fa03ImpAb) on-farm control parameters.

show the method of scientific thinking and hypothesis testing to compare one intervention to another (on-farm control versus abattoir control).

Since 1994 the Danish government and pork producers have implemented a progressive on-farm program (pre-harvest) of serological testing and management for high *Salmonella* prevalence in herds. At the same time, the abattoir in Denmark was improving their harvest processes, as was the case in most other developed countries. Circa 2004, policy makers were asking which program would provide the best hope of continued improvement, pre-harvest or post-harvest.

We developed a simulation model using best available data on the relationships between on-farm seroprevalence, carcass contamination by *Salmonella* and human salmonellosis. By exercising this model and comparing the results if only the pre-harvest program (Fig. 4) had been implemented (19% decrease from 1995 to 2003) versus if only the post-harvest program had been implemented (33% decrease, $p<0.05$; Fig. 5), we were able to conclude that most past and future improvements in public health benefit would arise from post-harvest efforts. So while both camps were correct, pre- and post-harvest efforts are beneficial, the relative impact of post-harvest efforts was greater.

Generic thinking

The last systems thinking skill I will mention briefly is generic thinking. It is the recognition that there is similar structure inherent in many of the systems where we work and live. Meadows (2008) offers useful examples of the generic systems behaviors in her chapter entitled, 'A brief visit to the systems zoo'. Some of the examples we have discussed, such as a self-limiting compounding growth, can be found in many situations such as economics and personal relationships, food production, epidemiology and pathogen ecology. For example, Covey's description of the 'emotional bank account' could be described as a draining feedback loop with a non-linear behavior (Covey, 1989). The quality of our human relationships can be viewed as a state variable full of goodwill. We can take a limited number of withdrawals from a person's goodwill. Once that state of goodwill reaches a certain 'low' threshold, surprising and unpleasant interactions may occur. This systemic behavior is similar to when an animal's immune system diminishes to a certain level leading to infection.

Conclusion

As noted, systems thinking and the systems approach are gaining more attention in food production. We must be careful not to make the same mistakes as may have been made in the business world. According to Forrester (1994),

'Systems thinking is in danger of becoming one more of those management fads that come and go. The term is being adopted by consultants in the organization and motivation fields who have no background in a rigorous systems discipline.'

Structurally changing our approach to problem solving and translating these concepts will take a tremendous personal and professional effort, beginning before the first year of veterinary school. Fortunately, others have made advances in general science education (Forrester, 1996; Draper, 2010). As Forrester (1994) notes, systems thinking is a 'door opener' that may lead decision makers to application of rigorous systems dynamic analysis. For this step we who work as or educate food-systems practitioners will need help. Many fields of engineering and some in management have the quantitative skills needed for detailed systems analysis.

Whether we choose to recognize and study them or not, the structures explained above exist in our world. There are flows, states, feedback loops, nonlinear relationships, oscillations and surprising system instabilities. Today, a practitioner's decision may affect more than one sick cow, and could impact a multi-million dollar corporation and/or the public health of a country. Many bad decisions can be made because there was no systems analysis. Should we not be willing to make a long-term commitment to retooling our mindset and educational efforts? The few references in this paper are only an introduction to leaders in systems thinking. My hope is to take us on a new journey.

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