University of Alberta

**A bioeconomic model of the broiler chicken supply chain**

by

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of *Doctor of Philosophy*

in

*Animal Science*

Department of Agricultural, Food and Nutritional Science

Edmonton, Alberta
Fall 2004

*Your file Votre référence*
*ISBN: 0-612-96048-X*
*Our file Notre référence*
*ISBN: 0-612-96048-X*

*Get it right or let it alone,*
*The conclusion you jump to may be your own.*

James Thurber, Further Fables for Our Time (New York, 1956)

## DEDICATION

To Martin and Nellie Zuidhof: your visionary "college fund" has borne fruit!
I wish you were here to share the moment.

## ACKNOWLEGEMENTS

The financial support of the Alberta Agricultural Research Institute, the Alberta Chicken Producers, the Alberta Hatching Egg Producers and Lilydale Poultry Co., is gratefully acknowledged. Thank you to the poultry industry for your support of the Alberta Poultry Research Centre. A healthy, functional research centre, the existence of which facilitated this work, is not easily achieved. Thank you to Alberta Agriculture, Food and Rural Development for support in the way of education leave, and financial support of many aspects of the research. Thanks to Doug Milligan for encouraging me to go back to school and recognizing the value of it for the broiler industry. Thanks to Michelle Follensbee for your support of the effort, and pressing me to set achievable goals. I'm done!

Thanks to my supervisory committee, particularly John Feddes, Bob Hudson and Tarja Joro. Your insights, direction, encouragement, and attention to scope were so valuable. Thanks to my poultry research colleagues, especially Frank Robinson and Rob Renema. You make poultry research stimulating and fun; in the words of Cynthia vdD-O, "You are without peer."

Thank you Sebrena, Marcus, Evan and Eliot, for your patience. Pretty soon you'll have your dad back, and we'll make up for lost time, K? Thank you, my dear bride Lucie, for the seasons where you took on so much more of the really important things in life because "Dad's holed up in the dungeon again". I love you. Thank you God for the ability to do this. Help me to find your purpose in it all.

## TABLE OF CONTENTS

## LIST OF TABLES

### Tables for Chapter Three:



### Tables for Chapter Four:



### Tables for Chapter Five:

**Tables for Chapter Six:**

**Tables for Chapter Seven:**

## LIST OF FIGURES

### Figures for Chapter One:



### Figures for Chapter Three:



### Figures for Chapter Four:



### Figures for Chapter Five:

**Figures for Chapter Six:**



**Figures for Chapter Seven:**

## LIST OF ABBREVIATIONS

BCSCM = broiler chicken supply chain model

DR = diminishing returns

FCR = feed conversion ratio

FFFEBW = feather- and fat-free empty body weight

HH = hen housed

PY = proportional yield

RMSE = root mean squares error

S = sigmoidal

SC = supply chain

SD = standard deviation

V-A = value-added

# CHAPTER 1. GENERAL INTRODUCTION

### *The poultry meat industry in Canada*

The poultry meat industry in Canada is a supply-managed system. It is managed by a producer-funded national body, the Chicken Farmers of Canada, whose primary responsibility is to ensure that Canada's 2,800 producers grow enough chicken to serve the primarily domestic market (Chicken Farmers of Canada, 2003). Farm cash receipts totaled $1.45 billion in 2002, approximately 4.2% of total farm cash receipts in Canada. Despite chicken's modest showing in these terms, Canadians in 2002 consumed more chicken meat (30.6 kg per person) than any other meat. Beef and pork consumption in the same year was 30.0 and 28.1 kg per person, respectively (Chicken Farmers of Canada, 2003). An increasing chicken consumption trend has been firmly entrenched for at least two decades. This trend has the potential to continue, as the per capita consumption of meat in Canada was less than 80% of American per capita meat consumption in 2002 (Chicken Farmers of Canada, 2003).

In contrast to the vertically integrated structure of the American poultry industry, the Canadian poultry industry is characterized by much smaller processing companies, many of which are producer-owned cooperatives. Processing plants and hatcheries are typically owned by these companies, but feed manufacturing, which contributes to approximately two-thirds of the total live cost of production, is independently owned and operated. Management decisions at the production level are generally poorly integrated with overall supply chain objectives.

### *The problem*

Genetic progress in meat-type chicken stocks has been dramatic over the past fifty years. High heritability of growth rate and feed conversion efficiency (Harris et al., 1985), short generation times, and high output of progeny have contributed to staggering rates of progress in broiler stocks. Havenstein and associates (2003a; 2003b) reported a four-fold increase in 42-d BW (Figure 1), and a six-fold increase in carcass weights as a result of selection programs between 1957 and 2001.

A correlated consequence of this progress has been poor reproductive performance in broiler parent stock (Brillard, 2001). There is a clear tradeoff of reproduction with broiler performance and yield (Robinson and Wilson, 1996). The supply chain overall benefits economically from high-yielding lines. Yet, the preferred strain choice for the broiler grower and processor is generally not as good for the hatching egg producer. The chick contribution to the total cost of meat production, though relatively small, is not well understood. A segmented management paradigm in the broiler supply chain further adds to controversy over the strain decision. In order to function optimally, the hatching egg producer must see the chick not as a final product, but as a stage in the production of chicken meat. Correspondingly, the supply chain must compensate hatching egg producers according to the value genetic stocks with poor reproductive performance add to overall performance. Understanding the economic consequences of the strain decision at each level of the supply chain can only help to turn a competition paradigm to one of cooperation. When all supply chain participants focus on important performance indicators relevant to the supply chain as a whole, greater improvements in efficiency can be achieved. To support the strain decision and fairly compensate all actors in the supply chain, the complexities of the system need to be understood. The purpose of the bioeconomic supply chain model that is the subject of this thesis is to elucidate costs and especially benefits of the commercial strain crosses available to the chicken meat industry, facilitating cooperative thinking and behaviour.

### *General objective*

The primary objective of this thesis was to develop and use a bioeconomic model to determine the economically optimal commercial broiler strain choice for whole-bird and value-added poultry markets.

### *Specific objectives*

1. To elucidate the effect of strain-specific biological variables, including reproductive performance and nutritional inputs, on chick production costs in the context of a hatching egg enterprise.
2. To determine broiler production costs, based on body composition and strain-specific growth parameters.
3. To characterize the yield dynamics of carcass parts from males and female broilers of six commercial strain crosses.
4. To determine, in the context of the whole supply chain, strain-specific costs and benefits of six commercial broiler strain crosses, by incorporating strain-specific hatching egg and broiler production costs and yields with an economic processing model.

## *Approach*

The current thesis describes the development of a bioeconomic broiler chicken supply chain simulation model. The model consists of three main modules, but its effectiveness results from linking the three modules together. The sub-models include a static hatching egg cost model, a broiler cost model, and a processing cost model. The static hatching egg model combines fixed costs related to capital requirements with variable costs that depend on biological raw materials (chickens!). Strain-specific performance data was employed. The broiler cost model receives strain-specific inputs from a dynamic, stochastic, and mechanistic broiler growth model. The processing cost model includes a stochastic mechanistic yield model that accounts for strain-specific variable costs and revenues, and combines these costs with fixed costs, which are independent of strain.

The three submodels are combined into a supply chain model to elucidate costs and benefits of six commercial strain crosses for each segment of the chain. The value of each strain cross in two supply chain market scenarios is estimated.

## *Summary*

The model shows clear differences in the importance of the strain decision based on market type. The model predicts that the strain choice represents a potential difference in profitability of $4.1M per year for a processing plant producing 400,000 kg/wk for a value-added market. In a whole bird market the model predicted that the strain decision would be worth approximately $1M. In a value-added market where a premium is extracted for breast meat, two strains (both with the same female parent) had substantially superior economic performance (Figure 2). This was due to improved yield in breast meat yield, particularly in males. The model predicted that at equivalent BW, males in the whole bird market were more profitable than females. In the value-added market scenario, female broilers were more profitable than males of equivalent BW, particularly at low BW. Because of substantial sex-specific differences in profitability in some strains, sex-separate rearing of broilers may prove to be profitable where multiple markets exist for the broiler supply chain. In a preliminary analysis using the model, an 11% improvement in profitability was predicted by channeling females to value-added markets to exploit their increased expression of breast muscle growth.

The relative value of these strains to the supply chain depends on the markets that are available. The strain choice must depend on overall profitability, and by incorporating strain-specific cost analysis in each segment of the chain, price negotiation and remuneration, particularly at the hatching egg level is facilitated.

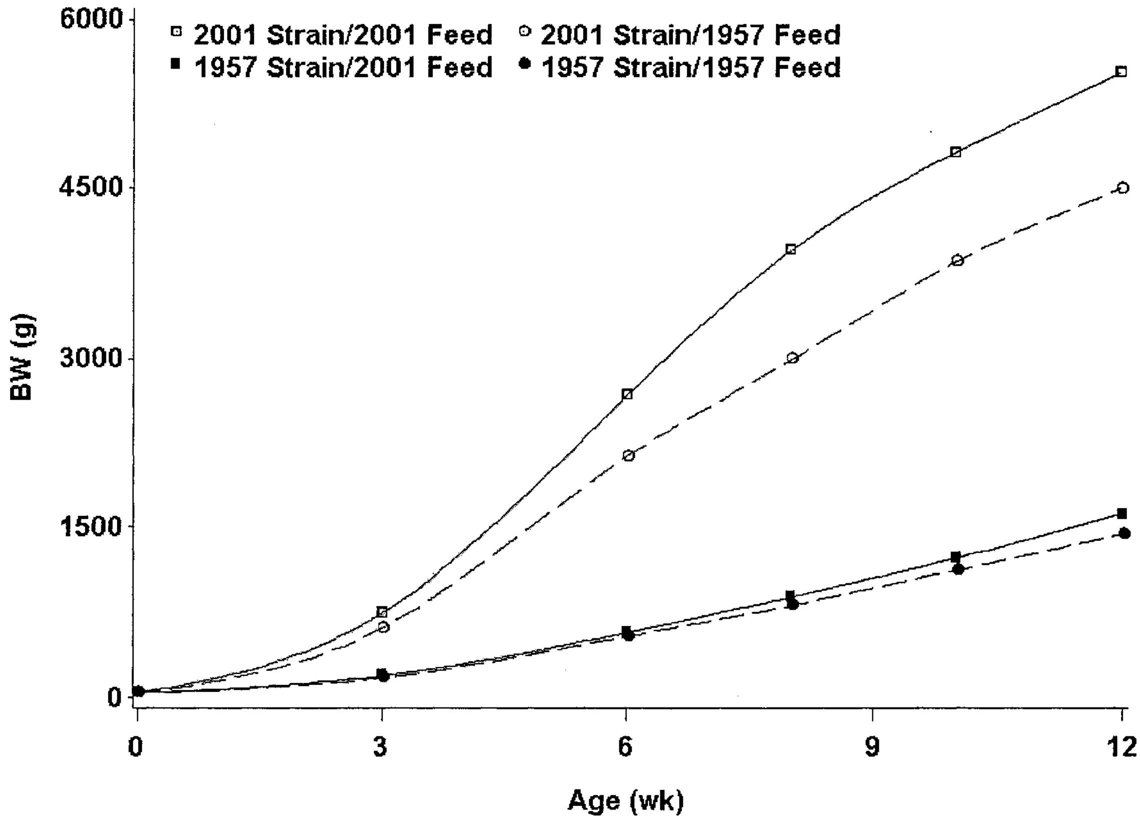


Figure 1. The result of 44 years of progress in broiler genetics and nutrition represented as BW profiles of random bred broilers unselected since 1957 and commercial (2001) broilers grown on feeds typical of 1957 and 2001 (data from Havenstein et al., 2003b).

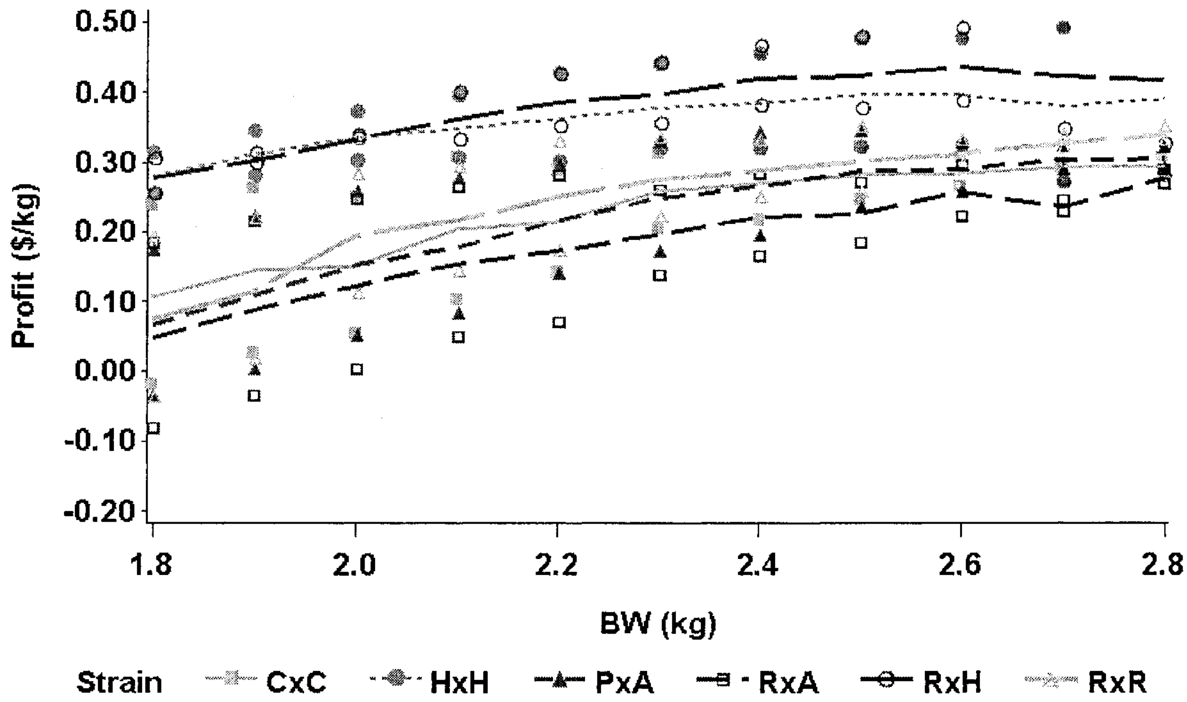


Figure 2. Effect of BW and strain on profitability of six strains of commercial broilers under a value-added processing scenario. Strains are denoted as male parent x female parent cross where A=Arbor Acres classic; C=Cobb 500; H=Hubbard HI-Y; P=Peterson; and R=Ross 308.

*References*

Brillard, J. P. 2001. Future strategies for broiler breeders: An international perspective. World's Poultry Sci. J. 57:243-250.

Chicken Farmers of Canada. 2003. Chicken Data Handbook.

Harris, D. L., M. K. Akbar, and C. R. Arboleda. 1985. System simulation for designing integrated broiler breeding programs. Pages 1-30 in the Proceedings of the 34th Annual National Breeders' Roundtable, St. Louis, Missouri.

Havenstein, G. B., P. R. Ferket, and M. A. Qureshi. 2003a. Carcass composition and yield of 1957 versus 2001 broilers when fed representative 1957 and 2001 broiler diets. Poultry Sci. 82:1509-1518.

Havenstein, G. B., P. R. Ferket, and M. A. Qureshi. 2003b. Growth, livability, and feed conversion of 1957 versus 2001 broilers when fed representative 1957 and 2001 broiler diets. Poultry Sci. 82:1500-1508.

Robinson, F. E. and J. L. Wilson. 1996. Reproductive failure in overweight male and female broiler breeders. Anim. Feed Sci. Tech. 58:143-150.

# CHAPTER 2. A FRAMEWORK FOR BROILER SUPPLY CHAIN MODELING

## *Introduction*

***Models.*** Most simply put, a model is a mimic. Models have played an important role in the development of thought. Rivett (1980) defines a model as

> *"...a convenient way of representing the total experience which we possess, of then deducing from that experience whether we are in the presence of pattern or law and, if so, showing how such patterns and laws can be used to predict the future".*

Models are everywhere. Children build models (towers) out of stones or blocks and through the process learn the principles (the presence of pattern and law) that will eventually lead them to understand the laws of gravity and thermodynamics. Blueprints are models that help planners and builders to visualize a final structure. Navigators use models (maps) to reach a destination safely and efficiently. Astronomers use models to explain and predict apparent movements of the moon, planets and stars. Einstein, through amazing abstract models (thought experiments), realized physical theories that have revolutionized the world. Models mimic reality in ways that help people understand the original. As Massoud (1998) put it, models simplify and put into familiar terms complicated phenomena, enabling the user to think much more clearly about the subject.

### *Mathematical models.*

Plato, in The Republic (translated by Grube, 1974) considered the (real) world as a model (an imperfect copy) of the really real. To Plato, mathematics is simply an abstraction – only the idea of numbers actually exists (Ule, 2002; why mathematics works is a very interesting question, but beyond the scope of the current discussion). Linear and nonlinear mathematical models mimic state or behavioural changes of substances or bodies, and can be used to predict their behaviour. Mechanistic models that reflect the complexity of an atom, cell, organism, or a system such as a supply chain can lead us to insights that would otherwise escape us. Levins (1966) wrote

> *"A mathematical model is neither a hypothesis nor a theory. Unlike the scientific hypothesis, a model is not verifiable directly by an experiment. For all models are both true and false... The validation of a model is not that it is 'true' but that it generates good testable hypotheses relevant to important problems."*

Models can adopt two of three strategies: generality, precision, or realism (Levins, 1966). Holling (Holling, 1998), describing the analytical (precision-focused) and integrative (big picture-focused) cultures of ecology, highlights the dangers of the two streams operating in isolation of each other. The danger of the analytical culture is to provide exactly the right answer for the wrong question; the danger of the integrative culture is to provide exactly the right question but a useless answer. As Levins proposed for population biologists, I agree that the best modeling approach for agricultural systems models, where the objective is to predict what will happen in the real world, is to sacrifice precision for generality and realism. Other approaches may be more appropriate for different applications. The current project is an attempt to integrate many precise answers from the analytical branch of biological research into a general framework that poses the right questions. Further development and parameterization will hopefully lead to right answers.

***Technology.*** Any child can flick a light switch and make practical use of the centuries of thought that finally led Edison to invent a light bulb. No understanding of positive and negative charges and the flow of electrons through a wire is required. Any fool driver (and I've seen some) can turn a key, step on an accelerator pedal, and be propelled down the freeway to the destination of choice. No knowledge of the kinetics of organic reactions is required. Technology is (by definition) the practical application of knowledge, or the manner of accomplishing a task using technical processes. There are innumerable ways to use technology, often with little knowledge of the underlying system. The aim of the technology developed in this thesis is to provide a simpler means of understanding the contribution of commercial strain crosses to supply chain economics. Very little knowledge about the growth of different chemical fractions of low temperature bioreactors (chickens) is required.

***System Models.*** Systems can sometimes be visualized as plumbing networks. Objects in a system behave like reservoirs (stocks) that can be filled (inflow) or drained (outflow) at rates controlled by valves (rate determining factors). The flow rates into and out of stocks can often be represented with simple mathematical relationships. Through understanding of how a more complex system works, these simple mathematical relationships can be linked together in a way that simulates interactions in a real system. The process of building a system model is a journey of discovery about how a system fits together and functions; the final model can be examined and manipulated in ways that the original cannot, often leading to insights that would otherwise go undiscovered.

***Types of models.*** Models are both descriptive and predictive. They are most useful when they are used to turn insights about what happened previously into predictions or hypotheses of what might happen in the future. The study of statistics and uncertainty combined with exponential progress in information technology has made it possible to harvest tremendous benefit from complex predictive models.

Models fall into three main categories. They can be any combination of static or dynamic; empirical or mechanistic; and deterministic or stochastic (Duan-yai, 1999). Static models deal with a single state at one point in time while dynamic models describe state changes over time. Empirical models describe a body or a system, often without due regard for underlying causes. Empirical models tend to be less robust than mechanistic models, which reflect the mechanisms or processes of the system being modeled. In this dissertation a combination of static (hatching egg production cost model) and dynamic (broiler growth and yield) models are exploited to infer the best strain choice. Models can be deterministic, predicting a single outcome, or stochastic, predicting a range of possible outcomes based on the reality of variability in inputs or responses.

The current model represents an attempt to describe the broiler chicken supply chain in a mechanistic manner, though there are some empirical assumptions such as the allometric growth rates of different chemical fractions of the broiler carcass. Parts of the current model are deterministic, such as the broiler and hatching egg cost models. Other parts are stochastic, such as the broiler growth model (which is required in the processing model), and can provide input for the broiler cost model. The model described in this thesis, then, is a dynamic, mechanistic and stochastic broiler chicken supply chain model.

***Bioeconomic models.*** A bioeconomic model is a special type of dynamic mechanistic model that incorporates an array of physical and biological states (*e.g.* increasing BW states of a growing animal) with which inputs (*e.g.* feed intake) can be linked. Bioeconomic models associate monetary values (*e.g.* the cost of feed) with physical and biological inputs, generating comprehensive economic summaries of biological processes such as the production of chicken meat. A deterministic bioeconomic model predicts a single outcome; a stochastic bioeconomic model predicts an array of outcomes, depending on how variability of input parameters is defined. With a stochastic bioeconomic model, the results of repeated simulations can be analyzed to infer the probability of a specific outcome (*e.g.* achieving >10% return on investment).

***Livestock models.*** Relatively simple models of growth have been developed that describe the overall growth of tissues (stocks) and organisms (sets of stocks). Growth theories have been naturally integrated with nutritional theories that address how nutrients (amino acids, fats, carbohydrates) consumed by the organism are partitioned into various tissues. The rates of partitioning vary by age and tissue type (allometry), with nutrient availability (*ad libitum* intake *vs.* fasting), or with metabolic state (*e.g.* compensatory growth). Nutrients reside in the organism for a time; some are excreted and recycled. Eventually the organism dies and all of the nutrients stockpiled in the organism are recycled.

***Production system models.*** It is not a great leap from the livestock system model to an economic model of production. Feed costs are a substantial part of the cost structure of the livestock industry. Feed is quite simply a mixture of grains and seeds and other organic and inorganic products with definable (with a fairly consistent degree of certainty) content of nutrients required by the animal, and a cost determined by supply and demand. Robust theories about growth and nutrient requirements make prediction (modeling) of feed intake possible. It is relatively simple to assign a cost to units of feed which are required to fill the energy and protein requirements of animals. Those costs can be added to other fixed and variable production costs, and voila! … an estimate of live production costs. By accounting for the nutritional costs of reproduction, this can be repeated for the parent stock. By further accounting for the costs and revenues associated with processing, the economics of the entire system can be brought to light.

***Modeling philosophy***

The foregoing description is greatly simplified for good reason: it is imperative not to lose sight of the objective of a model in the process of building it. Factors key to a model's ability to answer the question posed must remain in focus. There are an infinite number of combinations of factors that potentially affect the growth of a broiler chicken. There are infinitely more combinations of factors that affect the parent stock and the processing plant. As Levins (1966) alluded, the model builder must be disciplined, and remain focused on factors that are important to the relevant question.

A reasonable way to approach the supply chain model, and one that has been applied in the current project, is to start with a very simple model that includes only the factors that are required to answer the question. Take the case of profitability in the broiler chicken supply chain. The original question was, "Which commercial strain cross is the most profitable for the broiler chicken supply chain?" Profitability is a function of total revenues and total costs. Therefore, we need two numbers for each strain cross. If revenues (a function of conformation) or costs (a function of growth rate) are strain-dependant, they must be expanded to include relevant yield ratios or growth rates. Similarly, processing costs consist of plant-specific costs (fixed and variable) and raw material costs. Both of those must be expanded as needed to answer the relevant questions. The cost of the raw material (broiler chicken) can be expanded into an array of costs, including chick cost. A hatching egg production sub-model can be developed to feed that chick cost input.

Assuming that the answer to the relevant question (the most profitable strain cross) is simply one of economics, the answer must include strain-specific costs and revenues. Not every cost is strain-specific. Further, not every cost will be clearly definable. Because the system is biological, the question is overshadowed by a high degree of uncertainty. Feed ingredient quality, exposure to pathogens, resistance to pathogens, heat and cold stress, and pecking orders dictate that outcomes like body weight and carcass conformation will vary unpredictably. Where these factors are important, stochastic approaches can be applied. The likelihood of the occurrence of discrete events like a disease outbreak can be measured and incorporated. In the context of the strain decision, unless the probability of an outbreak is reasonably high, and that outbreak has strain-specific effects, it would be a waste of time to pursue. In this first iteration of a broiler chicken supply chain model, many such judgements have been made. Even though models yield powerful predictions about system behavior, it is important to recognize their limitations.

To answer the strain decision question, a basic broiler chicken supply chain model has been developed to include the effects of a wide variety of inputs and processes on the profitability of broiler meat production. Some of the variables included in the model have nothing to do with the strain decision. I was distracted by other agendas, like having producers and bankers analyze production costs at the hatching egg and broiler stages of the supply chain. Other variables that may be important, like differential responses to pathogenic challenges, have been omitted, simply because the scope needed to be reined in. These can be added modularly in the future.

Because of the size and complexity of a biological supply chain, a project like this has the potential to expand over decades. This project was an attempt to break new ground by tying together mechanistically the most important factors along the entire production chain that affect the profitability of different broiler genetic lines. Potentially, many models with different simplifications could be used to answer the same question:

> ..."*if these models, despite their different assumptions, lead to similar results we have what we can call a robust theorem which is relatively free of the details of the model. Hence our truth is the intersection of independent lies.*" (--Levins, 1966)

***A brief history of bioeconomic modeling in agriculture***

The practical benefits of many significant intellectual milestones have accumulated to a point where we can realistically develop and use complex models to support supply chain-level decision making. It is not the purpose of this introduction to provide an exhaustive review, but to highlight foundational contributions to growth and modeling research. It is appropriate to take a step back and acknowledge two early pioneers who began to prepare the way for livestock modeling centuries ago. Benjamin Gompertz is an outstanding figure in the field of growth modeling. Gompertz (Gompertz, 1825) was a pioneer in the field of nonlinear mathematical estimation of 'life contingencies'. His fundamental mathematical representation of growth has been adapted and improved, but the modern livestock growth modeling literature is covered with his fingerprints. However, even Gompertz' work would never have transpired were it not for the even more basic discovery of the incredible logarithm, first published by John Napier in 1614 (Weisstien, 1999). The significance of accomplishments like those of these two men (and there are many others that will remain unnamed) is truly remarkable.

The field of livestock modeling has innumerable contributors. There have been many notable contributors. Over the past 50 years there are several examples of comprehensive frameworks for thinking about growth and nutrient flows. Models such as the hydrostatic pressure model of nutrient partitioning priorities (Berg and Butterfield, 1976) provide novel and helpful means of thinking about processes that have many valid implications across livestock species. An outstanding pioneer in the field of growth modeling and nutritional theory, particularly poultry and swine, is Emmans. Emmans with key collaborators including among others Fisher, Gous and Kyriazakis, has prolifically published very useable descriptions of growth models and nutritional theory (Emmans, 1981; Emmans and Fisher, 1986; Emmans, 1989; Emmans, 1994; Hancock et al., 1995; Emmans, 1995; Gous et al., 1999) that have been instrumental in shaping the poultry modeling literature. Emmans, Fisher and Gous developed EFG[1], a commercial model of broiler growth in an economic context (EFG Software, 2000). The mechanics of the EFG model are extensively described in the scientific literature such that the modeling process can be replicated and the field advanced.

Many groups have attempted to optimize broiler production. Tremendous advancements in computer technology in the 1970's and 1980's resulted in a repertoire of literature on the subject. Though computer technology allowed much more elaborate analyses than had been possible previously, the limitations of computer technology to

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[1] EFG Software (Natal), P.O. Box 101476, Scottsville, 3209, South Africa

solve complex interactions between variables was acknowledged (e.g. Kennedy et al., 1976). A group led by Hurwitz and Talpaz led the difficult process of blending of poultry science with mathematics. They directed the poultry modeling agenda toward optimization. They reported optimal diet formulation strategies (Talpaz et al., 1986) and optimal growth curve strategies to take advantage of the phenomenon of compensatory growth (Talpaz et al., 1988). CHICKOPT™, a commercial application of their work, was acquired by Novus[2] in 1995. Further technical development by the original authors and a web interface led to the release of OmniPro® by Novus. It replaced the Ivey growth model (IGM®), used commercially by Novus prior to OmniPro®. Currently, BMP (broiler management program) software, which is a form of statistical profiling of commercial broiler performance based on factors ranging from genetics to nutritional inputs to grower effects is being implemented in the broiler industry. A similar program is being developed for breeder enterprises. Unfortunately for the academic community, the practical relevance of such technology has turned their focus more to commercial applications than to documentation of their methods.

The Wala group developed a proprietary enterprise optimization model (Wala et al., 2000). Their CAMERA model (Wala, personal communication) borrows heavily from the ideas of Calabotta (2001), and shifts focus from production parameters to bottom line economic parameters. Similarly, because of the commercial potential of such a model, nothing about this model's mechanisms has been published in the scientific literature.

Growth simulation models have also been developed for the pork sector. Notable leaders of these ventures are Black (CSIRO Animal Production, 2003), and Schinckel and

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[2] Novus International, Inc., 530 Maryville Centre Drive, St. Louis, MO 63141 USA

de Lange (1996). Like the EFG group, the AUSPIG group has published modeling mechanisms and relevant theories extensively. Results from animal performance simulations using the AUSPIG (CSIRO Animal Production, 2003) and Porkmaster (University of Guelph, 2004) models have been applied to optimize commercial swine production economics. Commercially useful models are much broader than biological models alone. According to Black (1993), animal models are likely to represent less than 20% of a commercially useful decision support package; models need to encompass the broader context of an enterprise, or supply chain.

***Economic models and genetic selection***

Geneticists have developed a system of economic weights in their genetic selection programs. Harris (1994) provided a great review illustrating the transition from selection based on visual traits to performance traits to economic traits. There are examples of economic weights applied to selection programs across livestock species, including poultry (Pasternak and Shalev, 1983; Akbar et al., 1985; Harris et al., 1985; Carte, 1986; Dekkers et al., 1995; Emmerson, 1997; Jiang et al., 1998), pigs (von Rohr et al., 1999; Hermesch et al., 2003), sheep (Conington et al., 2004), dairy (Goddard, 1998; Kluyts et al., 2003), and beef cattle (Ruvuna et al., 1992a; Ruvuna et al., 1992b; Basarab et al., 1999; Cozzolino et al., 2002). Incorporation of economics into selection programs requires comprehensive modeling because of uncertainties due to variability in the heritability of traits, and a great temporal disconnection from the final product.

The evolution of emphases in genetic selection programs to economics (Harris and Newman, 1994) needs to continue from a cost to a profit basis. In this regard, a foundational deterministic model has been published for poultry (Jiang et al., 1998;

Groen et al., 1998). With regard to broiler management, Allison and coworkers (1978) recommended a shift from least-cost ration formulation to admittedly more sophisticated models that incorporate the concept of least cost gain or maximum profit rations. This subtle shift from cost to profit focus represents a huge potential for improving competitiveness. It is a complex challenge that has not yet caught on in the broiler industry.

***Optimal harvesting strategy models***

In addition to genetic selection programs, bioeconomic models have been implemented primarily in the area of strategic optimal harvesting. Determining the best weight or age of harvesting depends on the size of the animal in question, the yield, and its market value. Examples of optimal harvesting models exist for fish (Hanson and Ryan, 1998), beef cattle (Amer et al., 1994; Williams and Bennett, 1995; Wilton and Goddard, 1996; Short et al., 1999; Nielsen et al., 2004). Melton and coworkers even used a bioeconomic model to predict the best strain choice and stocking rates for beef (Melton et al., 1994).

With very few exceptions, nutrient requirements for poultry have been defined in terms of maximizing growth, particularly of the whole carcass with increasing emphasis on breast meat (see review by Balnave and Brake, 2002); little attention has been paid to economic optimization. Similar strategies have been undertaken with environmental variables such as temperature (Timmons and Gates, 1986; May and Lott, 2001; Quentin et al., 2004). Optima in these studies are defined as a function of maximized meat yield at a certain age (many studies report only 42-d yield) instead of maximized profit, which is a function of meat yield, but also of age. Part of the problem with identifying an optimal slaughter time for broilers is that yield parameters are dynamic. While yield parameters are a function of genotype, age, BW, and nutrient intake they are not well defined in these terms (one of the gaps addressed by this thesis). Thus very few optimal harvesting models have been published for broilers.

Cravener and associates (1992) reported the effect of stocking rates on a profit per unit of growing space basis. Oguz and Parlat (2003) demonstrate through the use of a coefficient of economic efficiency (Total marginal net income / Marginal costs) that an economic optimum for the production phase can be determined. However, the approach was a static production level approach, and did not take into consideration the carcass values which change dramatically with time. Some optimal feeding strategies have been implemented to reduce the cost of feeding broilers to market weights (Kennedy et al., 1976; Talpaz et al., 1986; Talpaz et al., 1988; Gous, 2001). For turkeys, a commercial spreadsheet and supporting fact sheets have been developed to support optimal harvesting decisions, incorporating production costs and processing yields into a supply chain level analysis (Hybrid, 2004a-g).

The key to any optimization strategy is an appropriate performance indicator, or economic efficiency index. Examples include net return per unit of meat (e.g. $/kg meat), or net return per unit of capital per unit of time (e.g. return on investment). Sustainability of the poultry industry will require similar attention to the optimization of multiple objectives including economics, animal health, food safety and meat quality (Brillard, 2001; Akiba et al., 2001; Whitehead, 2002). DenOuden and associates (1997) attempted to balance pig welfare and associated costs with consumer preferences. They demonstrated the feasibility of this approach, finding that in Europe some additional welfare costs were acceptable to consumers.

***Transferring research into practice.***

Supply-chain level management in a competitive environment precludes the use of intuition alone for decision making. A more sophisticated approach to decisions is required to optimize profitability. Implementation of a mathematical modeling framework at Sadia, a producer of 3 million chickens and 11 million turkeys per year resulted in savings of $50 million over a three-year period (Taube-Netto, 1996). Implementation of optimization production planning models in China in two years increased crop and livestock profits by 12 and 54%, respectively (Zhao et al., 1991).

The fields of Operations Research and Management Science are the source of powerful tools that remain largely unapplied in the livestock research community (Roush, 2001). Sankaran and Luxton (2003), describing the impact of a supply chain level focus on attempts to optimize the New Zealand dairy industry, note that the aggregate of the decisions that are optimal for different actors in the supply chain are less than optimal for the industry as a whole. APSIM is a very powerful example of a modular integrated farming-systems simulation designed to predict economic and ecological outcomes of crop management decisions (Keating et al., 2003).

McCown (2001) provides an excellent discussion of the challenges of model implementation, describing the gap between scientific theory and real-world practice. It is naïve to think that the development alone of good models will result in their implementation. One of the approaches he recommends is a more comprehensive approach – a shift from the production system to the management system. Future agricultural models *do* need to take a more integrated approach. Even beyond management systems, markets, environmental, and social implications of decisions (Bland, 1999) are important components of agricultural supply chain decisions.

***The role of agricultural supply chain models***

Supply chain models by their nature condense superfluities of information into a form that makes decisions almost intuitive. Models that incorporate numerous variables in a mechanistic fashion, such that the economic consequences of complex and nonlinear relationships can be seen, provide the type of clarity decision makers need to position themselves competitively. They are the key to making quick accurate decisions that minimize organizational efforts and expenses implementing new technology opportunities (Calabotta, 2001). To optimize operations planning, attention must be paid to relevant performance indicators: cost controls and revenue maximization (Sankaran and Luxton, 2003) along the supply chain. To optimize supply chain performance, economic and social factors need to be considered and modeled. Though supply chain modeling is difficult to apply to systems with biological raw materials, large improvements in economic performance can be gained from embracing complexity and variation to support decisions.

The chapters that follow will systematically tackle the problem of analyzing economics through the broiler chicken supply chain. A breeder enterprise model, designed to incorporate the most important strain-specific performance parameters into an economic context will be described in chapter three. A dynamic broiler model will be described in chapter four. Costs that accrue in a strain-specific manner are estimated by simulating the growth of a variety of commercial strain crosses, and assimilated into the economic context of a broiler operation. The complexities of yield dynamics will be explored in chapter five. To support the strain decision, it is imperative to predict yield as accurately as possible. Thus, the statistical analysis of strategies is necessary to describe broiler yield mathematically with minimal bias. The strain decision will finally become feasible in chapter six, where a processing module assimilates infrastructure and variable costs with the breeder, broiler growth, and yield modules described in the preceding chapters. Finally, an analysis of the relative weights of production costs in the broiler and breeder sectors, and the way those costs trade off with profitability in various market scenarios will be discussed in chapter seven.

This broiler chicken supply chain model incorporates many of the most important complexities that arise due to the biological nature of the raw material. Some arguably important factors, such as the biological response to amino acid intake, however, have been excluded. Therefore some assumptions are necessary, for example, that nutritional inputs are adequate for birds to express the growth and yield rates defined in the model. Many opportunities remain to develop various parts of the model, but the discussion in the final two chapters demonstrates that in its current form it offers a powerful new set of optics for broiler supply chain decision makers and economists.

### *References*

Akbar, M. K., D. L. Harris, and C. R. Arboleda. 1985. Development of the relative economic weights for linear and quadratic bioeconomic objectives in commercial broilers. Poultry Sci. 65:1834-1846.

Akiba, Y., M. Toyomizu, K. Takahashi, and K. Sato. 2001. Nutrition: the key role for optimization of growth and carcass quality in broiler chickens. Asian-Australasian J. Anim. Sciences 14:148-163.

Allison, J. R., L. O. Ely, and S. V. Amato. 1978. Broiler profit maximizing models. Poultry Sci. 57:845-853.

Amer, P. R., R. A. Kemp, J. G. Buchanan-Smith, G. C. Fox, and C. Smith. 1994. A bioeconomic model for comparing beef cattle genotypes at their optimal economic slaughter end point. J. Anim. Sci. 72:38-50.

Balnave, D. and J. Brake. 2002. Re-evaluation of the classical dietary arginine : lysine interaction for modern poultry diets: a review. World's Poultry Sci. J. 58:275-289.

Basarab, J. A., J. R. Brethour, D. R. ZoBell, and B. Graham. 1999. Sorting feeder cattle with a system that integrates ultrasound backfat and marbling estimates with a model that maximizes feedlot profitability in value-based marketing. Can. J. Anim. Sci. 79:327-334.

Berg, R. T. and R. M. Butterfield. 1976. New concepts of cattle growth. New York, Halsted Press, a Division of John Wiley and Sons, Inc.

Black, J. L., G. T. Davies, and J. F. Fleming. 1993. Role of computer-simulation in the application of knowledge to animal industries. Austral. J. Agric. Res. 44:541-555.

Bland, W. L. 1999. Toward integrated assessment in agriculture. Agric. Syst. 60:157-167.

Brillard, J. P. 2001. Future strategies for broiler breeders: An international perspective. World's Poultry Sci. J. 57:243-250.

Calabotta, D. F. 2001. Risk-benefit assessment of technology transfer in the poultry industry. J. Appl. Poultry Res. 10:306-312.

Carte, I. F. 1986. Genetic-economics of chicken meat production. Proc. of the 3rd World Congress on Genetics Applied to Livestock Production, Lincoln, Nebraska. Institute of

Agriculture and Natural Resources.

Conington, J., S. C. Bishop, A. Waterhouse, and G. Simm. 2004. A bioeconomic approach to derive economic values for pasture-based sheep genetic improvement programs. J. Anim. Sci. 82:1290-1304.

Cozzolino, D., D. De Mattos, and D. Vaz Martins. 2002. Visible/near infrared reflectance spectroscopy for predicting composition and tracing system of production of beef muscle. Anim. Sci. 74:477-484.

Cravener, T. L., W. B. Roush, and M. M. Mashaly. 1992. Broiler production under varying population densities. Poultry Sci. 71:427-433.

CSIRO Animal Production. 2003. AUSPIG: A computer decision support system. http://www.auspig.csiro.au/; accessed July 2004.

Dekkers, J. C. M., P. V. Birke, and J. P. Gibson . 1995. Optimum linear selection indexes for multiple generation objectives with nonlinear profit-functions. Anim. Sci. 61:165-175.

Denouden, M., R. B. M. Huirne, A. A. Dijkhuizen, and P. Vanbeek. 1997. Economic optimization of pork production-marketing chains. 2. Modelling outcome. Livestock Prod. Sci. 48:39-50.

Duan-yai, S. 1999. Analysis of computer simulation models for the Thai broiler industry. Ph.D. Thesis. University of Queensland.

EFG Software, EFG Software (Natal), P.O. Box 101476, Scottsville, 3209, South Africa.

Emmans, G. C. 1981. A model of the growth and feed intake of ad libitum fed animals, particularly poultry. Computers in Animal Production. Occasional Publication No. 5. The British Society of Animal Production, Hillyer, G. M. C. T. Whittemore R. G. Gunn, eds.

Harrogate.

Emmans, G. C. 1989. The growth of turkeys. Recent Advances in Turkey Science. pp. 135-166. Butterworth & Co. Ltd, Essex, Great Britain.

Emmans, G. C. 1994. Effective energy - a concept of energy-utilization applied across species. Br. J. Nutr. 71:801-821.

Emmans, G. C. 1995. Problems in modelling the growth of poultry. World's Poultry Sci. J. 51:77-89.

Emmans, G. C. and C. Fisher. 1986. Problems in nutritional theory. Nutrient Requirements of Poultry and Nutritional Research. pp. 9-39. Butterworth & Co, Ltd, Cornwall, England.

Emmerson, D. A. 1997. Commercial approaches to genetic selection for growth and feed conversion in domestic poultry. Poultry Sci. 76:1121-1125.

Goddard, M. E. 1998. Consensus and debate in the definition of breeding objectives. J. Dairy Sci. 81(Suppl 2):6-18.

Gompertz, B. 1825. On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. Trans. Royal Phil. Soc. 115:513-585.

Gous, R. 2001. Modelling energy and amino acid requirements in order to optimise the feeding of commerical broilers. International Symposium ACVA (Spanish), Concordia, SC.

Gous, R. M., E. T. Moran Jr., H. R. Stilborn, G. D. Bradford, and G. C. Emmans. 1999. Evaluation of the parameters needed to describe the overall growth, the chemical growth, and the growth of feathers and breast muscles of broilers. Poultry Sci. 78:812-821.

Groen, A. F., X. Jiang, D. A. Emmerson, and A. Vereijken. 1998. A deterministic model for the economic evaluation of broiler production systems. Poultry Sci. 77:925-933.

Grube, G. M. A. 1974. Plato's Republic. Indianapolis, Hackett Pub. Co.

Hancock, C. E., G. D. Bradford, G. C. Emmans, and R. M. Gous. 1995. The evaluation of the growth parameters of six strains of commercial broiler chickens. Br. Poultry Sci. 36:247-264.

Hanson, F. B. and D. Ryan. 1998. Optimal harvesting with both population and price dynamics. Math BioSci. 148:129-146.

Harris, D. L., Akbar, M. K, and Arboleda, C. R. 1985. System simulation for designing integrated broiler breeding programs. 34th Annual National Breeders' Roundtable, St. Louis, Missouri.

Harris, D. L. and S. Newman. 1994. Breeding for profit - Synergism between genetic-improvement and livestock production (a review). J. Anim. Sci. 72:2178-2200.

Hermesch, S., E. Kanis, and J. J. Eissen. 2003. Economic weights for feed intake in the growing pig derived from a growth model and an economic model. J. Anim. Sci. 81:895-903.

Holling, C. S. 1998. Two cultures of ecology. Conservation ecology [online] 2:Art 4.

Hybrid. 2004a. Economic modeling #1: Using the Hybrid economic model. http://www.hybridturkeys.com/Media/PDF_files/Economic/Eco_1.pdf; accessed July 2004. Hybrid Turkeys, 650 Riverbend Dr., Kitchener, ON N2K 3S2, Canada

Hybrid. 2004b. Economic modeling #2: Law of diminishing returns. http://www.hybridturkeys.com/Media/PDF_files/Economic/Eco_2.pdf; accessed July 2004. Hybrid Turkeys, 650 Riverbend Dr., Kitchener, ON N2K 3S2, Canada

Hybrid. 2004c. Economic modeling #3: Feed cost and optimum killing weight. http://www.hybridturkeys.com/Media/PDF_files/Economic/Eco_3.pdf; accessed July 2004. Hybrid Turkeys, 650 Riverbend Dr., Kitchener, ON N2K 3S2, Canada

Hybrid. 2004d. Economic modeling #4: Breast meat value and optimum killing weight. Is bigger better? http://www.hybridturkeys.com/Media/PDF_files/Economic/Eco_4.pdf; accessed July 2004. Hybrid Turkeys, 650 Riverbend Dr., Kitchener, ON N2K 3S2, Canada

Hybrid. 2004e. Economic modeling #5 Cost and revenue: Optimum killing weight determination - "Is bigger better?". http://www.hybridturkeys.com/Media/PDF_files/Economic/Eco_5.pdf; accessed July 2004. Hybrid Turkeys, 650 Riverbend Dr., Kitchener, ON N2K 3S2, Canada

Hybrid. 2004f. Economic modeling #6 Market defined killing weights: "Is bigger better?". http://www.hybridturkeys.com/Media/PDF_files/Economic/Eco_6.pdf; accessed July 2004. Hybrid Turkeys, 650 Riverbend Dr., Kitchener, ON N2K 3S2, Canada

Hybrid. 2004g. Managing for profits. http://www.hybridturkeys.com/Media/PDF_files/Economic/Eco_7_Mng.pdf; accessed July 2004. Hybrid Turkeys, 650 Riverbend Dr., Kitchener, ON N2K 3S2, Canada

Jiang, X., A. F. Groen, and E. W. Brascamp. 1998. Economic values in broiler breeding. Poultry Sci. 77:934-943 .

Keating, B. A., P. S. Carberry, G. L. Hammer, M. E. Probert, M. J. Robertson, D. Holzworth, N. I. Huth, J. N. G. Hargreaves, H. Meinke, Z. Hochman, G. Mclean, K. Verburg, V. Snow, J. P. Dimes, M. Silburn, E. Wang, S. Brown, K. L. Bristow, S. Asseng, S. Chapman, R. L. Mccown, D. M. Freebairn, and C. J. Smith. 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agronomy 18:267-288.

Kennedy, J. O. S., B. H. Rofe, I. D. Greig, and J. B. Hardaker. 1976. Optimal feeding policies for broiler production: An application of dynamic programming. Austral. J. Agr. Econ. 20:19-32.

Kluyts, J. F., F. W. C. Neser, and M. J. Bradfield. 2003. Development of breeding objectives for beef cattle breeding: Derivation of economic values. South African J. Anim. Sci. 33:142-158 .

Levins, R. 1966. The strategy of model building in population biology. Amer. Scientist 54:421-431.

Massoud, T. F., G. J. Hademenos, W. L. Young, E. Gao, J. Pile-Spellman, and F. Vinuela. 1998. Principles and philosophy of modeling in biomedical research. FASEB J. 12:275-285.

May, J. D. and B. D. Lott. 2001. Relating weight gain and feed:gain of male and female broilers to rearing temperature. Poultry Sci. 80:581-584.

McCown, R. L. 2001. Learning to bridge the gap between science-based decision support and the practice of farming: Evolution in paradigms of model-based research and intervention from design to dialogue. Austral. J. Agric. Res. 52:549-571.

Melton, B. E., W. A. Colette, K. J. Smith, and R. L. Willham. 1994. A time-dependent bioeconomic model of commercial beef breed choices. Agric. Syst. 45:331-347.

Nielsen, B. K., A. R. Kristensen, and S. M. Thamsborg. 2004. Optimal decisions in organic steer production - a model including winter feed level, grazing strategy and slaughtering policy. Livestock Prod. Sci. 88:239-250.

Oguz, C. and S. S. Parlat. 2003. An econometric approach to prediction of optimal broiler production cycle using the coefficient of economic efficiency. J. Anim. Feed Sciences 12:315-324.

Pasternak, H. and B. A. Shalev. 1983. Genetic-economic evaluation of traits in a broiler enterprise: reduction of food intake due to increased growth rate. Br. Poultry Sci. 24:531-536.

Quentin, M., I. Bouvarel, D. Bastianelli, and M. Picard. 2004. What "requirements" for essential amino acids in broiler chickens? A critical survey of their determination and of some practical models. Productions Animales 17:19-34.

Rivett, P. 1980. The model in science. Model building for decision analysis. pp. 1-17. John Wiley & Sons, Ltd., Norwich.

Roush, W. B. 2001. An operations research approach to leveraging new technology opportunities. J. Appl. Poultry Res. 10:293-302.

Ruvuna, F., J. F. Taylor, J. P. Walter, J. W. Turner, and R. M. Thallman. 1992a. Bioeconomic evaluation of embryo transfer in beef production systems: I. Description of a biological model for steer production. J. Anim. Sci. 70:1077-1083.

Ruvuna, F., J. F. Taylor, J. P. Walter, J. W. Turner, and R. M. Thallman. 1992b. Bioeconomic evaluation of embryo transfer in beef production systems: III. Embryo lines for producing bulls. J. Anim. Sci. 70:1091-1097.

Sankaran, J. K. and P. Luxton. 2003. Logistics in relation to strategy in dairying - the case of New Zealand dairy. Int. J. Oper. & Prod. Mgmt. 23:522-545.

Schinckel, A. P. and C. F. de Lange. 1996. Characterization of growth parameters needed as inputs for pig growth models. J. Anim. Sci. 74:2021-2036.

Short, R. E., E. E. Grings, M. D. MacNeil, R. K. Heitschmidt, C. B. Williams, and G. L. Bennett. 1999. Effects of sire growth potential, growing-finishing strategy, and time on feed on performance, composition, and efficiency of steers. J. Anim. Sci. 77:2406-2417.

Talpaz, H., J. R. de la Torre, P. J. H. Sharpe, and S. Hurwitz. 1986. Dynamic optimization model for feeding of broilers. Agric. Syst. 20:121-132.

Talpaz, H., S. Hurwitz, J. R. de la Torre, and P. J. H. Sharpe. 1988. Economic optimization of a growth trajectory for broilers. Amer. J. Agr. Econ. 70:382-390.

Taube-Netto, M. 1996. Integrated planning for poultry production at Sadia. Interfaces 26:38-53.

Timmons, M. B. and R. S. Gates. 1986. Economic optimization of broiler production. Trans. ASAE 29:1373.

Ule, A. 2002. How we can apply the mathematics on the world? Filozofski Vestnik 23:25-51.

University of Guelph. 2004. PorkMa$ter information. http://www.aps.uoguelph.ca/~porkm/page2.html; accessed July 2004.

von Rohr, P., A. Hofer, and N. Kunzi. 1999. Economic values for meat quality traits in pigs. J. Anim. Sci. 77:2633-2640.

Wala, F., MacDonald, B., Segraves, M., Liu, J., and Meek, H. 2000. Managing for enterprise efficiency in broiler and turkey operations via enterprise optimization business processes. Midwest Poultry Federation- Annual Meetings, River Conference Center, St. Paul, Minnesota.

Weisstien. 1999. "Napierian logarithm" from MathWorld -- A Wolfram Web Resource. http://mathworld.wolfram.com/NapierianLogarithm.html; accessed July 2004.

Whitehead, C. C. 2002. Nutrition and poultry welfare. World's Poultry Sci. J. 58:349-356.

Williams, C. B. and G. L. Bennett. 1995. Application of a computer model to predict optimum slaughter end points for different biological types of feeder cattle. J. Anim. Sci. 73:2903-2915.

Wilton, J. W. and M. E. Goddard. 1996. Selection for carcass and feedlot traits considering alternative slaughter end points and optimized management. J. Anim. Sci. 74:37-45.

Zhao, Q. Z., C. Y. Wang, Z. M. Zhang, Y. X. Zhang, and C. J. Wang. 1991. The application of operations-research in the optimization of agricultural production. Oper. Res. 39:194-205.

# CHAPTER 3. A HATCHING EGG PRODUCTION MODEL

**Abstract**. A general hatching production enterprise model is described in this chapter. The model provides a way to standardize comparisons between management regimes and strains. A single farm component can be used for multiple production scenarios, enabling fair comparisons of the economics of different scenarios. A flock component captures the key biological parameters required in enterprise analyses. Through combination of these two components, the economic consequences of a wide variety of biological, management, and infrastructure options can be determined.

**Abbreviation key**: HH = Hens housed

## *Background*

The process of raising broiler parent stocks is often referred to as hatching egg production, or broiler breeding, and the parent stock are generally referred to as broiler breeders. Hatching egg production is a complex process that involves two main phases: raising pullets and cockerels to the age of sexual maturity (approximately 20 wk in duration), and a production phase (approximately 40 wk in the Canadian system) where male and female broiler breeders are housed together so that fertile eggs can be produced.

In the past century, broiler stocks have been heavily selected for growth rate and meat yield (Emmerson, 1997). One unintended consequence of this selection has been poor reproductive performance (Robinson and Wilson, 1996; Robinson et al., 1993).

Even so, the reproductive output of a single well-managed feed restricted broiler breeder hen typically exceeds 120 chicks. As chick output decreases, chick costs increase exponentially in the total cost of broiler production.

Several strain choices exist for the broiler industry. There are two main product classes, which excel either in their ability to reproduce or grow. Fast growing strains with high feed efficiency have excellent performance in the broiler barn, and generally higher meat yield. These products are typically favored by processors because they tend to be the most profitable in the North American marketplace. Slower growing strains usually have a slightly lower feed efficiency and lower yield, but are easier to manage. The parent stocks in lower performance broiler strains usually produce more hatching eggs with less management intervention.

In general, greater profitability in the processing sector can be achieved by choosing strains with reduced chick production and lower net returns in the broiler breeder sector. To maximize profitability along the supply chain and to fairly compensate hatching egg producers for less fecund strains, it is important to understand the relationship between input costs, productivity, and processing profitability farther down the supply chain.

Because of the complexity of the hatching egg sector, it is difficult to understand the effect of input costs and management decisions on the cost and value of hatching eggs and broiler chicks. A hatching egg production system model illuminates unit costs within the greater production cost structure, facilitating the decision of which strain is the best for a given marketplace.

### *Objective*

The objective of this chapter is to describe and simulate a hatching egg production system so that the effect of input costs on chick production can be better understood.

### *Model description*

***Overview.*** The model was developed and deployed in the Windows platform using Delphi[1]. The main purpose of the broiler breeder model is to function as a static production cost model. The static cost model consists of two main components: farm and flock. Separating the farm and flock information facilitates comparisons of flock performance independently, using a common production infrastructure (buildings and equipment). This makes objective comparisons between strains or management regimes possible by holding constant costs that are not strain-specific. A sensitivity analysis has been added to facilitate evaluations of the magnitude of the effects of various input costs on total production costs.

***Cost of production model.*** The static hatching egg production model combines fixed and variable costs of production with productivity and income. Generally, the model can be expressed as:

$$R = I - (C_f + C_v) \qquad [1]$$

where $R$ is an indicator of economic performance (net return); $I$ is a vector of income sources; $C_f$ is a vector of fixed costs; and $C_v$ is a vector of variable costs.

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[1] Borland Delphi Enterprise Version 7.0, copyright © 1883-2002 by Borland Software Corporation 100 Enterprise Way, Scotts Valley, Calif. 95066-3249 U.S.A.

***Farm component.*** The farm component contains inputs for capital costs ($C_c$), fixed costs ($C_f$), and scale parameters. These inputs are summarized in Table 1. A total investment ($\sum_{i=1}^{5} C_{ci}$) of $1,040,750 is calculated for the sample scenario. Parameters specified in the fixed costs vector of the farm component include interest on operating and capital loans, depreciation, insurance, and taxes. The total of all fixed costs ($\sum_{j=1}^{4} C_{fj}$) calculated from the inputs in Table 1 is $81,200/yr, or 34,354 per flock. A detailed summary of the example farm is appended (Appendix 1).

To attribute appropriate fixed costs to chick production, the farm component has two scaling parameters: cycle length ($T_c$) and number of flocks per cycle ($n$). The simplest analysis can be made with production and costs from a single laying flock. In this case, a cycle length equal to the average time between flock placements should be used. For example, if a hatching egg enterprise consists of a pullet barn into which chicks are placed every 22 wk, which supplies two laying barns which are filled alternately (every 44 wk), then a single flock ($n$ = 1) with a cycle length $T_c$ = 22 wk should be used. A total of 0.423 ($T_c$ / 52 wk/yr) of annual $C_f$ is attributed to one flock ($34,354 in this example). Alternatively, 44 wk of $C_f$ and production from two flocks ($T_c$ = 44; $n$ = 2); or 66 wk of $C_f$ and production from three flocks ($T_c$ = 66; $n$ = 3) could be used in a composite analysis. Any number of scenarios can be evaluated by specifying the number of flocks and the appropriate cycle length.

***Flock component.*** A flock is defined as the group of birds that are housed together in the laying facility. This is the most important functional unit of the hatching egg cost model. To standardize the definition of flock size and calculations based on the size of the flock, the number of hens housed (HH) is defined as the number of females alive at 24 wk. Egg and chick production rates are based on the number of HH. The number of saleable chicks is defined as chicks that hatch and are of sufficient quality[2] to be used as broilers. The model expresses costs and revenues on a per-yr, per-cycle, and per-HH basis because they are useful from a management perspective. Costs, income, and margins are also expressed on a per-saleable chick basis. Since the saleable chick is the unit that continues down the supply chain, costs expressed in these units can be readily compared across scenarios.

Flock-specific productivity parameters and sample input values are presented in Table 2. Total variable costs ($\sum_{k=1}^{7} C_{vk}$) using these parameters are presented in Table 3, and total \$140,923 for the flock.

Three income sources are included in the model. The primary income is calculated on a per-saleable chick basis. In the example scenario total income ($\sum_{m=1}^{3} I_m$) totals \$191,166, using a value of \$0.385/saleable chick. Spent hen income can be calculated using a price per kg (live weight). The spent body weight inputs and number of birds alive at the end of lay are used to calculate total salvage value of the flock. For the flock scenario presented in Table 2 and Table 3, a total salvage value of \$2,723 can be calculated for the flock, or \$6,436/yr. Income from miscellaneous sources such as the sale of compost or double-yolked eggs can be input as well. A value of \$120 for the flock is

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[2] Quality standards may vary, depending on demand for chicks, but the subjective quality measure usually excludes only deformed or lame chicks, chicks with unhealed navels, or those lacking vigor.

included in the example scenario. A detailed report from the sample scenario is appended (Appendix 2).

***Financial reporting.*** The model provides a facility to summarize production costs by combining any flock with any farm scenario. Care must be taken to ensure that flock size is appropriate for the farm infrastructure scale, and that the number of flocks matches the number specified in the farm component. A financial report is generated using the fixed costs from the farm component, and production and variable cost information from the flock. Data are combined and summarized on a per-yr, per-cycle, per-HH, and per-saleable chick basis. A break-even chick price is calculated as the total production costs on a per-saleable chick basis. Break-even production is calculated as the number of chicks per HH that are required to achieve a net return of $0.00. Return on investment (ROI) is calculated as the ratio of net return to the total investment.

The following weighted averages are calculated for the various production parameters: Chicks placed, HH, mortality (0 to 24 wk, and 24 wk to the end of lay), salvage carcass weights, peak production, peak hatch, egg production, cull eggs, hatchability, cull chicks, and saleable chick. A detailed summary of the sample farm and flock scenarios is appended (Appendix 3).

### *Sensitivity Analysis*

***Chick production.*** Sensitivity analysis can be conducted using any farm and flock combination. For the active scenario, a range of inputs for the number of saleable chick, feed cost, feed intake, female chick cost, male chick cost, utility cost, or labour costs can be entered. Independent sensitivities of net return, break-even price, break-even production, or ROI to these input variables can be easily viewed graphically.

One of the primary differences between strains is the number of chicks that can be produced by each hen housed. Figure 1 illustrates the sensitivity of the total cost of producing each saleable chick and return on investment on the number of saleable chick produced. As chick numbers decrease it is clear that there will be an increasing rate of increase in total cost. There is a non-linear inverse relationship between the number of saleable chick produced and economic performance indicators expressed on a per saleable chick basis (Equation 2):

$$C_{sc} = \frac{(C_v + C_f)}{SC} \qquad [2]$$

where $SC$ is the number of saleable chicks, $C_{sc}$ is the total cost expressed on a per saleable chick basis, and $C_v + C_f$ is the sum of fixed and variable costs per HH. The derivative of this relationship (Equation 3) yields the rate at which the total cost changes as a function of chick numbers.

$$C_{sc}' = \frac{-(C_v + C_f)}{SC^2} \qquad [3]$$

For example, the total cost of production at a level of production of 80 saleable chicks/HH is $C_f + C_v = \$41.35$. At this level of production the rate at which increased production alters the cost per saleable chick is -\$41.35/(80 saleable chick)$^2$ = -\$0.0065/saleable chick for each extra saleable chick produced. The rate of change at a production level of 160 saleable chicks/HH is -\$42.69/(160 saleable chick)$^2$ = -\$0.00167/saleable chick for each extra saleable chick produced.

***Input costs.*** Input costs affect chick costs in a linear fashion. A summary of linear regression coefficients describing the sensitivity of selected production costs (per HH) is presented in Table 4. Replacement pullet costs on a per HH basis are slightly more than the cost per chick due to mortality (ratio of 1.03:1). Increased cockerel costs affect the cost per HH at a ratio of 0.096:1. In the scenario described an increase in feed cost of $1/tonne results in a cost increase of $0.053/HH. An increase in feed intake of 1 kg per female results in a cost increase of $0.235/HH. Increases in costs expressed on a per flock basis (*e.g.* utilities and labour) increase per-HH costs by $0.251 per $1000 increment.

***Strain comparison***

A strain comparison was conducted using data provided by breeding companies regarding the target performance of their breeders. The selected strains represent the majority of the strain choices in the North American broiler market. Strain crosses are quite common, and saleable chick costs could be estimated by combining any female performance data with data from the male parent of choice. Strain-specific input variables and a summary of the economic outcomes are presented in Table 5.

Combining the base farm scenario with strain-specific flock inputs yielded a substantial range in chick costs from $0.325 to $0.358, or approximately 10%. This translates to a difference in net return of $43,017 for a single flock. To justify the more expensive strain choice, improved profitability farther down the supply chain must compensate for the extra costs at the hatching egg level.

***Summary***

Reduced chick production has an increasing effect on cost of production as production decreases. This has important implications for strain decisions that often have chick production and meat production as competing objectives. The breakpoint in the decision analysis can only be determined in the context of the entire supply chain.

The hatching egg model described in this chapter provides a consistent way to report and analyze flock costs. The model allows for ready comparisons across enterprises varying greatly in scale. This approach enables fair comparisons of the benefits and costs of genotypes or management regimes. It is important to standardize production costs that often otherwise hide the true effects of a strain or management decision.

Table 1. Capital and fixed cost inputs and scale parameters for the hatching egg cost model.

| Parameter | Description | Value |
| --- | --- | --- |
| *Scale parameters* | | |
| $T_c$ | Cycle length = proportion of yr for which infrastructure costs are accrued in analysis | 22 |
| $n$ | Number of flocks placed per cycle | 1 |
| *Capital costs* | | — $ — |
| $C_{c1}$ | Total cost of production buildings [A] | $326,500 |
| $C_{c2}$ | Cost of all equipment required for production | $304,250 |
| $C_{c3}$ | Total cost of land | $150,000 |
| $C_{c4}$ | Cost of non-production facilities | $175,000 |
| $C_{c5}$ | Mobile equipment [B] | $85,000 |
| *Fixed costs* | | — $/yr — |
| $C_{f1}$ | Interest [C] | $6,250 |
| $C_{f2}$ | Depreciation [D] | $63,750 |
| $C_{f3}$ | Insurance | $8,000 |
| $C_{f4}$ | Taxes | $3,200 |

[A] One pullet barn, one stud barn, and two laying barns totaling 2,555 $m^2$ of barn space.
[B] Emergency backup power generator, tractor, truck, etc.
[C] Interest on a $100,000 operating loan at 6.5%/yr
[D] Annual depreciation rates of 5% on buildings, 10% on equipment, and 20% on motorized equipment

Table 2. Flock productivity inputs for a hatching egg production cost model.

| Parameter | Description | Parameter value |
|---|---|---|
| Hens housed (HH) | Hens alive at 24 wk | 4,000 |
| Eggs (#/HH) | Eggs sent to hatchery | 152.4 |
| Cull eggs (#/HH) | Eggs culled, primarily for size (<52 g) | 0.0 |
| Hatch (chicks/HH) | Total number of chicks hatched | 126.5 |
| Cull chicks (#/HH) | Chicks culled or otherwise not saleable | 4.2 |
| Chicks (#/HH) | Saleable chicks (hatch-cull chicks) | 122.3 |

Table 3. Summary of variable costs and income in hatching egg static production cost model.

| Parameter | Description | Value ($/cycle) |
|---|---|---|
| *Variable costs* | | |
| $C_{v1}$ | Chick cost [A] | 21,779 |
| $C_{v2}$ | Feed cost [B] | 49,149 |
| $C_{v3}$ | Utilities / fuel [C] | 20,000 |
| $C_{v4}$ | Repair / maintenance | 2,877 |
| $C_{v5}$ | Labour [D] | 30,500 |
| $C_{v6}$ | Board fees / marketing [E] | 8,064 |
| $C_{v7}$ | Other variable costs [F] | 1,354 |
| *Income* | | |
| $I_1$ | Saleable chicks [G] | 184,800 |
| $I_2$ | Salvage value of breeder flock [H] | 2,951 |
| $I_3$ | Miscellaneous income [I] | 240 |

[A] 4,200 female, 400 male, and 80 spiking male chicks at $4.65 per female chick, and $6.50 per male chick, with 4% supplied free.

[B] Feed cost based on intakes of 12.13 and 17.25 kg per bird for females and males, respectively, during rearing, and 36.40 and 24.50 kg per bird for females and males, respectively, during lay. Weighted feed costs $240/metric tonne for pre-lay feeds, and $234/metric tonne for layer feeds.

[C] Electricity, gas, fuel, and communications

[D] Management and hired labour costs.

[E] Provincial and national levies of 0.0168 per egg set

[F] Litter, veterinary, vitamin, antibiotics, and miscellaneous costs

[G] Based on income from 4000 hens at a production rate of 120 saleable chicks per hen, and a price of $0.385/saleable chick.

[H] Salvage income calculated as 3,800 hens at 4.13 kg; 300 original males at 4.98 kg; and 39 spiking males at 4.35 kg at the end of the laying cycle processed for $0.17/kg.

[I] Income from sale of composted litter and unsettable eggs

Table 4. Sensitivity of total cost to input variables.

| Variable | Sensitivity [A] ($/HH) |
|---|---|
| Average feed cost ($/t [B]) | 0.053 |
| Feed intake by females (kg/HH) | 0.235 |
| Pullet chick cost ($/each) | 1.032 |
| Cockerel chick cost ($/each) | 0.096 |
| Utilities ($1000/flock) | 0.251 |
| Labour ($1000/flock) | 0.251 |

[A] Sensitivity is the magnitude of change in of total cost per HH with a one-unit increase of the independent variable.

[B] Metric tonne

Table 5. Strain-specific broiler breeder production parameters[1] and economic outcomes for strain comparison analysis.

| Parameter (as of 60 wk) | Ross 308 | Ross 508 | Ross 708 | Cobb 500 | AA Plus | Hubbard HI-Y |
|---|---|---|---|---|---|---|
| Female traits | | | | | | |
| Total Eggs/HH | 158.3 | 155.8 | 155.7 | 159.0 | 161.4 | 172.0 |
| Hatching Eggs/HH[2] | 152.4 | 150.0 | 146.7 | 154 | 153.4 | 163.4 |
| Hatchability (%) | 83 | 84.5 | 86 | 85 | 84 | 83 |
| Chicks/HH | 126.5 | 126.8 | 125.5 | 130.9 | 128.9 | 135.6 |
| Saleable chicks/HH (2% free) | 122.3 | 122.6 | 121.3 | 126.7 | 124.7 | 131.4 |
| Feed (kg/female) | 54.95 | 53.67 | 51.95 | 50.27 | 51.24 | 50.00 |
| BW (Hens, kg) | 3.79 | 3.63 | 3.54 | 3.95 | 3.81 | 3.55 |
| Male traits | | | | | | |
| Male feed (kg/male) | 54.05 | 54.05 | 54.05 | 54.00 | 50.44 | 50.00 |
| BW (Roosters, kg) | 4.765 | 4.765 | 4.765 | 4.814 | 4.720 | 4.545 |
| Economic outcome | | | | | | |
| Total cost ($/chick) | 0.358 | 0.355 | 0.355 | 0.338 | 0.344 | 0.325 |
| Return on Investment (%) | 3.609 | 3.958 | 3.875 | 6.100 | 5.270 | 7.742 |

[1]Adapted from the following sources:

http://www.ross-na.aviagen.com/docs/308%20Breeder%20Mgt.pdf; accessed June 2004.

http://www.ross-na.aviagen.com/docs/Male%20Breeder%20mgmt.pdf; accessed June 2004.

http://www.ross-na.aviagen.com/docs/508%20Breeder%20mgmt.pdf; accessed June 2004.

http://www.ross-na.aviagen.com/docs/Ross%20708%20Breeder%20Supplement.pdf; accessed June 2004.

http://www.aa-na.aviagen.com/docs/AA%20Plus%20Breeder%20Supplement%20Feb%2023.pdf; accessed June 2004.

http://www.cobb-vantress.com/contactus/brochures/Guide_Breeder_English_Paginated.pdf; accessed June 2004.

Hubbard Farms, 1994. HI-Y Breeder Management Guide. Walpole, NH 03608, USA.

[2] Hatching eggs > 52 g.

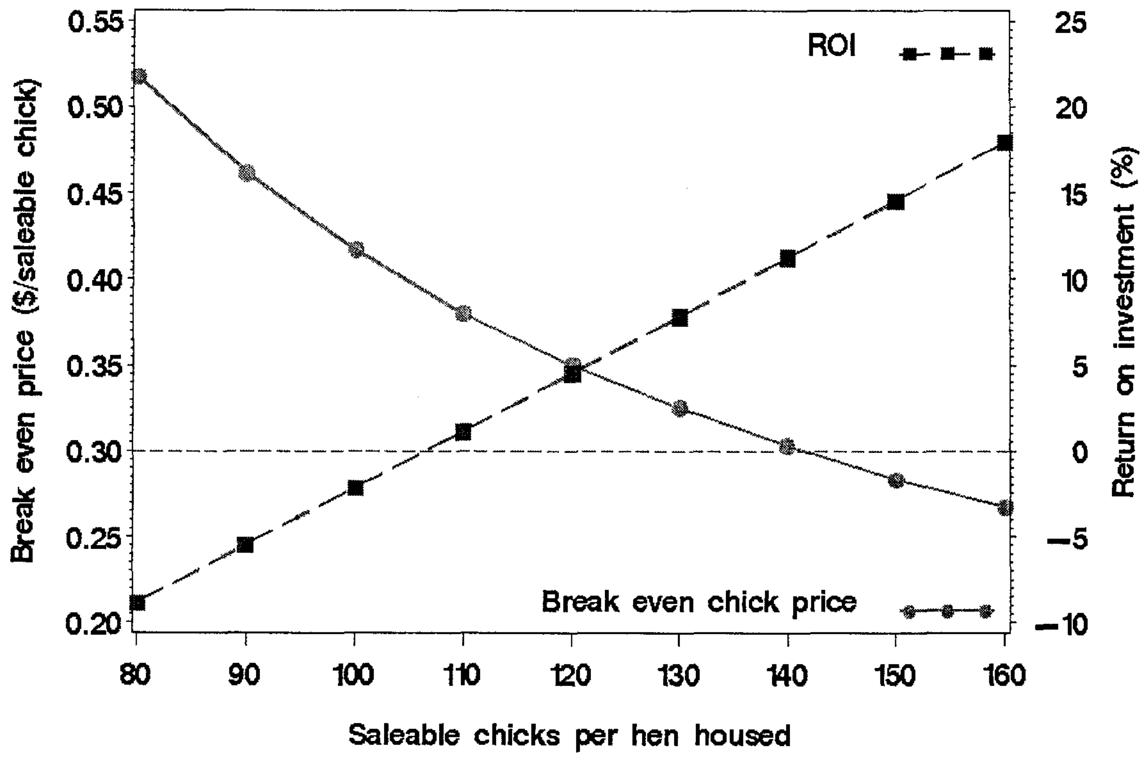


Figure 1. Sensitivity of net return and return on investment to the number of saleable chicks per hen housed.

### *References*


Emmerson, D. A. 1997. Commercial approaches to genetic selection for growth and feed conversion in domestic poultry. Poultry Sci. 76:1121-1125.

Robinson, F. E. and J. L. Wilson. 1996. Reproductive failure in overweight male and female broiler breeders. Anim. Feed Sci. Tech. 58:143-150.

Robinson, F. E., J. L. Wilson, M. W. Yu, G. M. Fasenko, and R. T. Hardin. 1993. The relationship between body-weight and reproductive efficiency in meat-type chickens. Poultry Sci. 72:912-922.

Appendix 1. Sample farm input data and fixed costs summary.

FARM SETUP REPORT

**Farm ID : Sample Farm**

**Quota information**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Annualized quota units | 10,000 | Utilization | 87.00% | Flocks placed per cycle | 1 | Cycle Length (wk) | 22 |

| Barn ID | Type | Size (sqft) | Cost ($/sqft) | Equip cost ($/sqft) | Capacity (# animals) |
|---|---|---|---|---|---|
| 1 : Pullet | Pullet | 7,000 | 11.000 | 5.000 | 3,889 |
| 2 : Layer 1 | Layer | 8,000 | 12.500 | 15.000 | 4,444 |
| 3 : Layer 2 | Layer | 8,000 | 12.500 | 15.000 | 4,444 |
| 4 : Stud | Stud | 4,500 | 11.000 | 6.500 | 2,500 |
| Weighted Totals | | 27,500 | 11.873 | 11.064 | |

**Capital Costs**

| | | | | | | Investment | $/Annualized Quota Unit |
|---|---|---|---|---|---|---|---|
| Land | 100 | acres @ | 1,500 | $/acre | | 150,000 | 0.0000 |
| Base Quota | 10,000 | units @ | 0.00 | $/unit | | 0 | 0.0000 |
| Purchased Quota | 0 | units @ | 0.00 | $/unit | | 0 | 0.0000 |
| Facilities - rearing | | | | | | 126,500 | 0.0000 |
| - laying | | | | | | 200,000 | 0.0000 |
| Equipment - rearing | | | | | | 64,250 | 6.4250 |
| - laying | | | | | | 240,000 | 0.0000 |
| Installation of utilities / services | | | | | | 0 | 0.0000 |
| House | | | | | | 0 | 0.0000 |
| Shop | | | | | | 175,000 | 0.0000 |
| Stand-by Generator | | | | | | 25,000 | 2.5000 |
| Mobile equipment (tractor/truck) | | | | | | 60,000 | 6.0000 |
| **Total Investment** | | | | | | **1,040,750** | **104.0800** |

**Financial Costs**

9.610 % of investment financed
6.250 % weighted interest rate

| Monthly Payment | $/month | $/year | $/cycle |
|---|---|---|---|
| Interest portion | 521 | 6,250 | 2,644 |
| Principal portion | 8,097 | 97,168 | 41,109 |
| Total Payment | 8,618 | 103,418 | 43,754 |

**Depreciation**

| | %/year | $/year | $/cycle |
|---|---|---|---|
| Buildings | 5.00 | 16,325.00 | 6,907.00 |
| Equipment | 10.00 | 30,425.00 | 12,872.00 |
| Mobile | 20.00 | 17,000.00 | 7,192.00 |
| Quota | 0.00 | 0.00 | 0.00 |

**Fixed costs**

| | $/year | $/cycle |
|---|---|---|
| Insurance | 8,000 | 3,385 |
| Taxes | 3,200 | 1,354 |
| Total depreciation | 63,750 | 26,971 |
| Interest | 6,250 | 2,644 |
| **Total Fixed Costs** | 81,200 | 34,354 |

Appendix 2. Ross 308 flock input data and variable costs summary.

## FLOCK REPORT

**Flock ID : Ross 308** **Farm ID : base farm scenario.bbf**

**Production Information**

| Bird data | Females | Males | Males (spiking) |
|---|---|---|---|
| Strain | Ross 308 | Ross | Ross |
| Growing barn | 1: Pullet | 1: Pullet | 1: Pullet |
| Laying barn | 2: Layer 1 | 2: Layer 1 | 2: Layer 1 |
| Chicks placed | 4,200 | 400 | 80 |
| Mortality (to 24 wk) | 4.76% | 12.50% | 12.50% |
| Number at 24 wk | 4,000 | 350 | 70 |
| Mortality (24 wk to end) | 5.00% | 14.29% | 44.29% |
| Spent BW (kg) | 3.790 | 4.765 | 4.765 |

**Production data**

| | # per day | % | per HH |
|---|---|---|---|
| Peak production | 3,400 | 85.00% | 0.8500 |
| Peak hatch | 3,230 | 95.00% | 0.9500 |
| Total eggs | 2,903 | 72.57% | 152.40 |
| Cull eggs | 0 | 0.00% | 0.00 |
| Total hatch | 2,410 | 83.01% | 126.50 |
| Cull chicks | 80 | 2.00% | 4.20 |
| Saleable chicks | 2,330 | 81.01% | 122.30 |

**Dates**

| | Females | | Males | | Spiking males | |
|---|---|---|---|---|---|---|
| | Date | Age (wk) | Date | Age (wk) | Date | Age (wk) |
| Hatch date | 9/26/2002 | | 9/26/2002 | | | |
| Placement date | 9/26/2002 | 0.0 | 9/26/2002 | 0.0 | | 0.0 |
| Photostimulation date | 2/14/2003 | 20.1 | 2/14/2003 | 20.1 | | 0.0 |
| Transfer date | 2/13/2003 | 20.0 | 2/13/2003 | 20.0 | | 0.0 |
| Date at 50% production | 4/9/2003 | 27.9 | | | | |
| Peak production date | 5/8/2003 | 32.0 | | | | |
| Peak hatch date | 6/14/2003 | 37.3 | | | | |
| Marketing date | 11/5/2003 | 57.9 | 11/5/2003 | 57.9 | | 0.0 |

BCSCM 2.45 7/19/2004 Page 1

## FLOCK REPORT

**Flock ID : Ross 308** **Farm ID : base farm scenario.bbf**

**Feed**

| | Females | | Males | | |
|---|---|---|---|---|---|
| | Cost ($/tonne) | Consumption (kg/HH) | Cost ($/tonne) | Consumption (kg/male) | Total feed consumption (g/saleable chick) |
| Starter | 256.00 | 1.200 | 256.00 | 2.250 | 11 |
| Grower | 239.00 | 9.465 | 239.00 | 12.850 | 87 |
| Prelay | 234.00 | 1.460 | 234.00 | 2.150 | 13 |
| Lay I | 234.00 | 17.000 | 234.00 | 12.800 | 148 |
| Lay II | 234.00 | 14.674 | 234.00 | 8.900 | 126 |
| Lay III | 234.00 | 11.151 | 234.00 | 15.100 | 102 |
| Total | | 54.950 | | 54.050 | 488 |

**Variable Costs**

| | free | $/unit | units | $/year | $/cycle |
|---|---|---|---|---|---|
| Chick (f) | 4.00% | $4.650 | /each | 44,366 | 18,779 |
| Chick (m) | 4.00% | $6.500 | /each | 5,909 | 2,500 |
| Spiking males | 4.00% | $6.500 | /each | 1,182 | 500 |
| Vaccines /veterinary | | | | 2,000 | 846 |
| Feed | | | | 132,824 | 56,195 |
| Growing | | $240.15 | /tonne | 30,955 | 13,096 |
| Laying | | $234.00 | /tonne | 101,868 | 43,098 |
| Utilities | | | | 47,273 | 20,000 |
| Labor | | | | | |
| Hired | | | | 20,091 | 8,500 |
| Management | | | | 52,000 | 22,000 |
| Litter / Nesting materials | | | | 1,200 | 508 |
| Levy (on settable eggs) | | $0.0168 | /egg | 19,426 | 8,219 |
| Repairs | | | | 6,800 | 2,877 |
| **Total Variable Costs** | | | | 333,090 | 140,923 |

## FLOCK REPORT

**Flock ID : Ross 308** **Farm ID : base farm scenario.bbf**

**Income**

| | | $/year | $/cycle |
|---|---|---|---|
| Saleable chicks | $0.3850 /chick | 445,172 | 188,342 |
| Spent hens | $0.1700 /kg | 6,436 | 2,723 |
| Miscellaneous | | 240 | 102 |
| **Total Income** | | 451,848 | 191,166 |

Appendix 3. Financial summary combining breeder flock with farm infrastructure costs.

## BREEDER FINANCIAL REPORT

Farm : Sample Farm
Flocks : Ross 308

| **Summary** | $/year | $/cycle | $/HH | $/AQU | $/Chick |
|---|---|---|---|---|---|
| Total cost | 414,290 | 175,277 | 103.57 | 41.43 | 0.3583 |
| Total income | 451,848 | 191,166 | 112.96 | 45.18 | 0.3908 |
| Net return | 37,558 | 15,890 | 9.39 | 3.76 | 0.0325 |
| Cash flow (before principal payment) | 101,308 | 42,861 | 25.33 | 10.13 | 0.0876 |
| Cash flow (after principal payment) | 4,140 | 1,752 | 1.03 | 0.41 | 0.0036 |
| **Cost summary** | | | | | |
| Fixed costs | 81,200 | 34,354 | 20.30 | 8.12 | 0.0702 |
| Chick cost | 51,477 | 21,779 | 12.87 | 5.15 | 0.0445 |
| Feed cost | 132,824 | 56,195 | 33.21 | 13.28 | 0.1149 |
| Utilities / fuel | 47,273 | 20,000 | 11.82 | 4.73 | 0.0409 |
| Repair / maintenance | 6,800 | 2,877 | 1.70 | 0.68 | 0.0059 |
| Labour | 72,091 | 30,500 | 18.02 | 7.21 | 0.0623 |
| Board fees (levy)/other marketing costs | 19,426 | 8,219 | 4.86 | 1.94 | 0.0168 |
| Other variable costs | 3,200 | 1,354 | 0.80 | 0.32 | 0.0028 |

| | |
|---|---|
| Break even price | $0.358 per Saleable chick |
| Break even production | 113.8 Saleable chicks per Hen Housed |
| Debt servicing ratio | 1.04 |
| Return on investment | 3.61% |

BCSCM 2.45 7/19/2004 Page 1

## BREEDER FINANCIAL REPORT

| Income | $/year | $/cycle | $/HH | $/AQU | $/Chick |
|---|---|---|---|---|---|
| Saleable chicks | 445,172 | 188,342 | 111.29 | 44.52 | 0.3850 |
| Spent hens | 6,436 | 2,723 | 1.61 | 0.64 | 0.0056 |
| Miscellaneous | 240 | 102 | 0.06 | 0.02 | 0.0002 |
| **Total Income** | 451,848 | 191,166 | 112.96 | 45.18 | 0.3908 |

**Benchmarks**

| Production | Females | Males | Males (spiking) |
|---|---|---|---|
| Chicks placed | 4,200 | 400 | 80 |
| Mortality (to 24 wk) | 4.76% | 12.50% | 12.50% |
| Number at 24 wk | 4,000 | 350 | 70 |
| Mortality (24 wk to end) | 5.00% | 14.29% | 44.29% |
| Spent BW (kg) | 3.790 | 4.765 | 4.765 |

**Production benchmarks (weighted averages)**

| | percent | per HH |
|---|---|---|
| Peak production | 85.00% | 0.8500 |
| Peak hatch | 95.00% | 0.9500 |
| Egg production | 72.57% | 152.40 |
| Cull eggs | 0.00% | 0.00 |
| Hatch | 83.01% | 126.50 |
| Cull chicks | 2.00% | 4.20 |
| Saleable chicks | 81.01% | 122.30 |

| Quota Utilization | Allowed | Actual (this analysis) |
|---|---|---|
| Annualized quota units (hens) | 10,000 | |
| Quota cycle length (wk) | 22 | |
| Pullets placed | | 4,200 |
| Hens at 24 wk | 3,681 | 4,000 |
| Placements per cycle (flocks) | 1 | 1 |
| Utilization (%) | 87.00 | 94.55 |

# CHAPTER 4. A BIOECONOMIC MODEL OF BROILER CHICKEN PRODUCTION

**Abstract.** This chapter describes a general broiler production enterprise model which includes important economic and biological parameters. Two key components of the model are a static cost model and a dynamic growth model. The cost model provides a framework for generating cost of production snapshots, particularly suited to alternative scenario evaluations. Using a Gompertz growth model, and an allometric approach to carcass component growth, bird-specific energy requirements are estimated. Using an energy-based nutrient requirement approach, growth-associated costs are integrated with enterprise level economics. Combination of the two components enables dynamic analysis of the economic potential of a range of broiler types. Built-in sensitivity and stochastic analysis capabilities enable decision makers to investigate alternative scenarios with pre-implementation feedback on likely economic outcome distributions of their decisions. The model provides a framework for consistent analysis and prediction of economic consequences of management decisions.

Abbreviation key: FCR = feed conversion ratio; SD = standard deviation

### *Background*

Canada's broiler industry, the ninth largest in the world in 2002, produced 938 million kg, worth $35.7 billion, and representing 4.2% of Canada's total farm cash receipts (Chicken Farmers of Canada, 2003). After a very strong 20 year trend of increasing per capita chicken consumption in Canada, chicken overtook beef as the most consumed meat by Canadians for the first time in 2002 (Chicken Farmers of Canada, 2003). The US chicken industry is the largest in the world, producing more than 16 times as much chicken as Canada in 2003 (FAOSTAT data, 2004), is an ever-present reminder of the importance of remaining competitive. To be competitive, the chicken supply chain in Canada must be able to make complex strategic and operational decisions well.

Broiler chicken production involves a large number of variables and complex interaction between variables. The U.S. broiler chicken industry has adopted a highly integrated structure to coordinate decision-making and improve profitability along the supply chain. The Canadian chicken industry is not as integrated, and there is little centralized control over decisions regarding nutrition and management. Decisions at feed mill or farm levels, made independently to optimize individual performance, result in sub-optimal practices for the supply chain.

In complex systems like the broiler supply chain, computer simulation models can be very helpful analytical tools. This paper describes a bioeconomic model of broiler chicken production. The model provides a robust framework with which to consistently analyze or predict the economic consequences of management decisions.

***Objective***

With the ambition of aiding complex economic decisions in the broiler supply chain, the objective of this chapter is to provide a sound basis for integrating the biological nature of the raw material in the broiler supply chain with the economic framework of broiler chicken production systems. Analytical procedures described in this paper are designed to elucidate the effects of biological variability to support management decisions that at the broiler production enterprise level in the context of supply chain economies. The intent is to provide a robust framework for supply chain context analyses.

### *Model overview*

To facilitate broad implementation on personal computers, the model has been developed with Delphi[1], and deployed in the Microsoft Windows platform as a stand-alone program. A trial version is posted at http://www.poultryresearch.ca/bcscm. There are two main components in the model: a static production cost model, with an economic analysis section for sensitivity and stochastic analyses; and a dynamic, mechanistic, stochastic broiler chicken growth model, the outputs of which can be scaled to and linked to any static cost scenario.

### *Cost of production model*

The cost of production model is a static economic model of a single broiler cycle. The cost model consists of five major sections: benchmarks, fixed costs, variable costs, income, and summary. To increase analytical flexibility, summarized production data are required as input. The benchmarks section is used to establish the scope of the broiler enterprise. Key inputs in this section include: either the number of kg of production or the number of chicks to be placed in the current cycle; chick BW; live BW at processing; cycle length (growing plus cleanout); mortality and condemnation rates; and the value of facilities and equipment. Using these inputs, the model calculates the number and total

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[1] Borland Delphi Enterprise Version 7.0, copyright © 1883-2002 by Borland Software Corporation 100 Enterprise Way, Scotts Valley, Calif. 95066-3249 U.S.A.

live weight of live birds marketed; chicks required; stocking density; and capital costs for the operation. Placement date, marketing date and strain information are collected because they are useful for statistical purposes, but are not used in any economic analyses or calculations. To maintain a constant level of total production for the enterprise for analytical purposes, the static cost model adjusts the number of chicks placed for mortality and condemnations. This enables the model to evaluate identical sized units, taking into consideration all scenario-specific mortality and condemnation data, without biasing economic performance by differences in the total weight marketed.

Fixed cost inputs include depreciation rates, loan information, insurance, and taxes. Depreciation rates are applied to building and equipment values. Total fixed costs are calculated and reported on a per-year, -cycle, and -kg live basis.

Variable cost inputs include per-bird chick, vaccination, sexing, and catching costs; monthly utility costs; cycle-specific veterinary, labor, and miscellaneous costs; and annual repair costs. In the static part of the model, feed conversion ratio (FCR) is input directly to the model. From FCR and total gain (*live market BW - chick BW*), the program calculates total feed intake on a per-bird basis. This allows greater analytical flexibility since live market BW and FCR can be altered more easily than feed intake data. Up to five diets are allowed (e.g. starter, grower, two finisher diets, and other inputs such as whole wheat). For each diet, the unit cost is input directly; intake is also input for each of the diets except one. Intake for one of the diets is calculated based on market BW, FCR and the intake of the other diets, forcing the BW and FCR variables to reconcile. In the automated stochastic and sensitivity analyses, the calculated amount of this diet is the only amount that fluctuates in response to changes in FCR. The model calculates the per-bird cost of each diet. Feed cost and all of the other variable costs are then presented on a per-kg, -cycle, and -year basis.

The income section of the model is a straightforward accounting of income on a per-kg live BW basis. Base income, with the option of a bonus or penalty, is calculated per-cycle and -year. Miscellaneous income can be entered on a per-cycle or -year basis, and calculated on a live per-kg basis. All income sources are summarized.

***Summary.*** Income, expenses, margins, and cash flow are summarized on a per-cycle, -year, and -kg live basis. Margins over feed and chick, variable, and total costs are calculated as *revenue-expenses*. Cash flow is calculated as the total income less total cash expenses (*i.e.* depreciation is not a cash expense). Break-even price is reported as the total cost of production. Break even price for cash flow is reported as the total of all expenses except depreciation. For benchmarking purposes, net return is also calculated as the margin over total cost on a per-bird, -kg, and -square foot basis.

### *Broiler Simulation*

***Scope.*** The broiler simulation is a dynamic mechanistic growth model that estimates strain- and sex-specific costs of production based on growth patterns of individual birds. User interface inputs to the growth model include the number of chicks placed, target market BW, and flock composition (pick from a list of males and females of various strain crosses). Nutritional inputs include the energy level of the feed (kcal/kg), and the age to which each ration is fed. By default, all feed rations contain 3100 kcal/kg. Rations are fed as three phases: 0 to 21 d; 22 to 35 d; and 36 d to end of simulation.

In the current paper, bird type refers to any combination of sex and strain. Gompertz growth parameters for males and females of six commercial strain crosses (12 bird types) reported by Wang and Zuidhof (2004) are used to calculate live BW and yield. The strains are coded as: PxA, RxA, CxC, HxH, RxH, and RxR, where the first and second letters represent the paternal and maternal parent lines, respectively. The paternal parent lines are P=Peterson, R = Ross, C=Cobb, and H=Hubbard. The maternal parent lines are A=Arbor Acres FSY, C=Cobb 500, H=Hubbard HI-Y, and R=Ross 308. Any ratio of bird types can be simulated. A utility is provided to modify and define growth parameters. This is necessary because some performance characteristics improve as much as 3-4% per year (Havenstein et al., 2003).

In the present model, potential growth is described, unconstrained by nutrition or environment. Deterministic or stochastic scenarios can be simulated. In deterministic simulation, an individual for each selected bird type is assigned mean growth parameters and simulated once. Flock performance is based on average performance of the bird types selected. In stochastic simulation, growth parameters are chosen stochastically (from a normal distribution) for each bird of a specified flock size and composition. In stochastic and deterministic simulation, growth, nutrient requirements, and feed intake required to support growth are calculated on a daily time step until market age is reached or exceeded. The simulation ends when the mean flock BW exceeds the target market BW. The cost of feeding is based on simulated feed intake. The model assumes that the nutritional requirements for the defined growth curves are met, and that broiler feed intake precisely matches the energy requirements of each bird. Production parameters including BW, feed consumption, FCR, mortality, are determined for the flock.

Relevant production parameters from the growth model can be evaluated independently, or scaled to any static economic model scenario to evaluate production costs in an enterprise context. Variables that can be linked to the static model include chick BW, intake of each ration, market BW, the number of chicks placed, age at market BW, FCR, and mortality.

***Growth simulation.*** A form of the Gompertz (1825) growth model described by Emmans (1981), has been modified to include individual random variation (Wang and Zuidhof, 2004). The Gompertz function is a double exponential function that is popular for broiler growth simulation (Emmans, 1995). If initial (hatching) BW is known, estimation of only two biologically relevant parameters (mature BW and rate of maturing) is required. Although i(Hancock et al., 1995)t has been criticized for inflexibility because of a fixed inflection point (Darmani Kuhi et al., 2003; Narushin and Takma, 2003), it has been implemented because of its simplicity and biological relevance (Gous et al., 1999).

Feathers grow at faster rates than the rest of the body, and have different nutrient requirements. For this reason, many broiler models simulate growth of the body and the feathers separately (Hurwitz, 1980; Martin et al., 1994; Hancock et al., 1995; Stilborn et al., 1997). This approach has also been taken in the current model where growth of the body and feathers is simulated separately, both by the Gompertz function, then summed to obtain BW.

The Gompertz model described by Wang and Zuidhof (2004) used in the current model has the form

$$W_t = (W_m + u)exp^{-exp^{-b(t-t^*)}} \qquad [1]$$

where $W_t$ is the BW (g) of the bird at time $t$ (d); $W_m$ is the mean mature BW (g) for a bird type (sex- and strain-specific); $u$ is a measure of variation of individuals within bird type from $W_m$, with an expected value (mean) of 0 (g) and variance of $\sigma_u^2$; $b$ is a rate of maturing ($d^{-1}$); and $t^*$ is age (d) at maximum growth rate (point of inflection). This equation can be rearranged to calculate age at market BW. The equation can also be rearranged to solve for $t^*$. Using chick BW at time $t = 0$ (*i.e.* $W_t = W_0$), the age at maximum growth rate can be calculated using the expression

$$t^* = ln(-ln(W_0/(W_m + u)))/b \qquad [2]$$

Differentiation of the Gompertz function (Emmans, 1981) yields equation 3, such that daily growth (daily time step: $\delta t = 1$ d) can be described using only 3 parameters: $b$ and $W_m + u$.

$$\frac{\delta W}{\delta t} = W_t \times b \times \ln\left(\frac{W_m + u}{W_t}\right) \qquad [3]$$

The growth rate in equation 3 was used to accumulate BW and the weight of feathers.

The Gompertz growth parameters and associated variance estimates for twelve broiler types estimated by Wang and Zuidhof (2004) are included stochastically in the model. Each simulated chick is assigned a hatch BW and a mature BW. Hatch BW are assigned using random draws from normal distributions with user-specified means and standard deviations (SDs). Mature BW parameters are drawn randomly from bird type-specific normal distributions with means $W_m$ and SDs $\sigma_{W_m}$. Because the rate of maturing $b$ is correlated with $W_m$ (see Figure 1), $b$ is calculated as:

$$b = a + mW_m \qquad [4]$$

where $a$ = -5.655E-02 and -6.071E-02, and $m$ = 2.72E-06 and 3.86E-06 for males and females, respectively. Feather growth parameters are chosen in the same manner.

Once the parameters have been chosen, growth for each bird is simulated on a daily time step. Growth is partitioned into lean tissue, fat, ash and water according to linear relationships describing their relative growth over time. These relationships have been estimated based on data from an experiment described elsewhere (Zuidhof, 2004). Allometric function estimates for males (Figure 2) and females (Figure 3) are summarized in Table 1.

***Allometric relationships.*** Metabolizable energy required for protein and fat deposition are determined from allometric relationships – the relative growth of various chemical parts to the whole body. In an experiment described elsewhere (Zuidhof, 2004), initial body protein, lipid, and ash content were determined to be 0.1423, 0.0680, and 0.0204, respectively. Initial feather weight across strains was 1.1 g. Dynamic lipid:protein ratios for males and females were calculated (equation 5) as a function of age as

$$Y_t = \alpha + \beta * t \qquad [5]$$

where $Y_t$ is one of three gain ratios (fat:total, protein:total, and ash:total gain ratios); $\alpha$ and $\beta$ are linear coefficients, and $t$ is age (d). The balance of the gain is assumed to be water. Coefficient estimates are summarized in Table 1. Feather growth was assumed to be 90% protein (Stilborn et al., 1997).

***Feed intake.*** Talpaz (personal communication[2]) posed an interesting and important question for the modeler: 'Does a bird grow because it eats, or eat because it grows?' Typically, growth is considered a response to eating. For the purposes of modeling, it is

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[2] Prof. Hovav Talpaz, CEO, LIDM Software Systems, Ltd., 143 Glil-Yam 46905 Israel

useful to think about this in reverse. The current model takes the approach that birds have potential to grow, and they eat to achieve that potential.

Feed intake simulation is based on two assumptions: 1) dietary nutrients are balanced in relation to nutrient requirements of the birds; and 2) birds consume sufficient feed to meet their nutrient requirements. Metabolizable energy requirements for maintenance, lean and feather growth, and fat deposition are estimated based on growth potential. The metabolizable energy requirement for maintenance ($ME_m$) is calculated according to equation 6 (adapted from Zoons et al., 1991)

$$ME_{mt} = maW_t^b \qquad [6]$$

where $ME_{mt}$ is metabolizable energy requirement for maintenance (kcal/d) at time $t$ (d); $a$ is a scaling variable (kcal/d); $W_t$ is BW at time $t$; $b$ is the degree to which net energy for maintenance depends on BW; and a linear coefficient $m$ (default value = 1.0) has been added so that the maintenance energy requirement can be proportionally scaled by the user.

The term $W_t^b$ is commonly referred to as metabolic BW. Historically, the value of $b$ has been estimated as 2/3 (Leeson and Summers, 2001), which is the approximate ratio between the surface area and body mass of an animal. For poultry, a generally accepted value for $b$ is 0.75 (Zoons et al., 1991; Chwalibog, 1991; NRC, 1994; Buyse et al., 1998; Leeson and Summers, 2001). The special case of $b=1$ represents a linear relationship between BW and maintenance energy requirements. For rapidly growing animals, values of $b$ exceeding 1, even as high as 2.0 have been suggested for rapidly growing animals (Zoons et al., 1991). Values of $b$ greater than 1 would be unstable with large BW. Because of the high metabolic rate of rapidly growing broiler chickens, and pragmatically, to account for energy expended for all processes other than fat and lean tissue deposition, a value of 1.0 is used for *b* in the current model. A utility is provided to customize the value of the maintenance energy coefficients.

In poultry, metabolizable energy requirements are typically 18% higher than net energy requirements in well balanced diets, and up to 30% for practical diets (Leeson and Summers, 2001). This is due to heat loss as a result of the metabolism of feed. This represents a weighted combination of a 30% heat production for proteins, 15% for carbohydrates, and 10% for fats. The NRC (1994) implicitly recommends 134 kcal/d per unit of metabolic BW for layers. For broilers, standard values for *a* range from 100 to 108 kcal/d per unit of metabolic BW (Zoons et al., 1991; Leeson and Summers, 2001), with some estimates as high as 191 kcal/d (Zoons et al., 1991). In the current model, a lower value of 101.2 kcal was used, in combination with a value of 1.0 for *b*.

Energy costs of lean tissue and fat deposition are also calculated. On a dry matter basis, a value of 14.35 kcal/g of protein, and 13.40 kcal/g of fat deposited has been reported (Zoons et al., 1991). In a comparison of published models of broiler energetics, values of 8.03 to 11.95, and 13.38 are suggested for lean and fat deposition, respectively (Shalev and Pasternak, 1998). In the current model, default values for energy costs of protein and lipid deposition are 10.0 kcal/g and 13.38 kcal/g, respectively, resulting in realistic feed intake prediction.

***Mortality.*** In the stochastic model, there are two options for simulating mortality. A weekly mortality pattern may be defined by the user, or an automatic mortality pattern can be simulated. The automatic pattern is generated using a modified Grosskopf and Matthaus (1990) methodology. The method is summarized mathematically as

$$M_t = \frac{\exp^{-0.1412t}}{Q} + 0.0547(\exp^{0.0877({W_t}^2 D - W_t^{0.005t} D W_t (0.9+1.1^{-\Delta T_t}))} \qquad [7]$$

where $M_t$ is the probability of mortality (%) at age $t$ (d); $Q$ is a chick quality score in the range of 1 (poor) to 10 (best); $W_t$ is BW at age $t$; $D$ is stocking density in the range of 0-30 birds/m$^2$; $\Delta T_t$ is the deviation of actual growing temperature (C) from target (*actual-target*) at age $t$.

For each day of the simulation and for every "live" individual, a random number is drawn from a uniform distribution between 0 and 100. If the value is less than the mortality probability prescribed for that day, then the individual is "dead" for the rest of the simulation. Feed costs accrue only to "live" individuals. Handling mortality in this way simulates the inefficiency of feeding birds that die in a commercial situation. A mortality-corrected feed conversion rate reported by the program is calculated by basing the total intake on the birds that survive to the end of the simulation.

### *Modeling experiments*

***Sensitivity analysis.*** A sensitivity analysis was conducted to determine the effect of mortality on total cost of production, break even income to meet cash flow needs, and margins over feed and chick costs, total costs, and all costs. Using a base economic scenario (Appendix 1; 5% mortality scenario shown), the level of mortality was altered from 0 to 50% in 2.5% increments, and the economic response was determined.

***Stochastic analysis.*** To determine the effect of variation in two parameters on economic outcome distributions, a stochastic analysis was conducted. In each scenario average mortality was 5%, and average FCR was 1.8. Only SD was changed for both variables. Two levels of variation in mortality (SD = 1% or 2%), and two levels of variation in FCR (SD = 0.1 or 0.2) were implemented in a 2x2 factorial arrangement, such that all combinations of the SDs were represented in four scenarios. For each scenario, 1000 draws were made independently for both mortality and FCR. Normal distributions for mortality and FCR, respectively, were: scenario A: N(5%,1%) and N(1.8,0.1); scenario B: N(5%,1%) and N(1.8,0.2); scenario C: N(5%,2%) and N(1.8,0.1); and scenario D: N(5%,2%) and N(1.8,0.2). The design of the analysis showing the arrangement of the scenarios is inferred in Table 3.

The economic context in Appendix 1 was also used for this analysis. All other inputs, were equal in all scenarios. To evaluate the effect of performance variation on exposure to economic risk, the probability of achieving a specified risk was determined. The specified risk was defined arbitrarily as a total cost of production exceeding \$1.05/kg. A standardized Z-statistic was calculated as *Z=(1.05-mean)/SD*. Using the PROBNORM function of SAS (SAS System, 2001), the probability of an outcome of total cost greater than \$1.05/kg was estimated, based on the distribution of outcomes for each scenario.

***Comparison of commercial broiler types.*** To compare cost of production of males and females of six commercial broiler strain crosses, growth of each bird type was simulated to target market BW of 1.8 to 2.9 kg, in 0.1 kg increments. With the exception of mortality, which was 0% in this analysis, the economic context of the analysis is reported in Appendix 1. Data were analyzed using the MIXED procedure of SAS (SAS System, 2001). Total cost of production was considered the dependent variable, strain and sex were main effects, and BW was a covariate in the analysis. Since each flock was simulated individually, they were considered independent. Differences between means were considered significant at $P<0.05$.

### *Results*

***Sensitivity analysis.*** The results of the sensitivity analysis (Table 2) demonstrated an increasing rate of increasing expenses (exponential) as mortality increased, and corresponding decreases in profitability (margins over feed and chick costs, variable costs and total costs). This analysis did not take feed costs into consideration; only the chick cost as a proportion of total costs was accounted for. Further, placements were adjusted by the model such that a total of 147,404 kg were produced in each scenario. The sensitivity analysis demonstrates the ability of the static model to evaluate the isolated effects of changes in specific parameters on the economics of production.

***Stochastic analysis.*** The distributions of outcomes in the stochastic analysis are presented graphically in Figure 4. Exposure to the predetermined negative outcome of expenses totaling greater than $1.05/kg is presented in Table 3. Changing variation in mortality from 1% to 2% resulted in a 2% increase in exposure to the high risk condition. Increasing the SD of FCR from 0.1 to 0.2 resulted in a 17% or 13% increase in the likelihood exposure to the specified risk, depending on variability in mortality.

***Comparison of commercial broiler types.*** The results of the simulations of twelve bird types are presented in Table 4. BW, sex, strain, and the interaction between sex and strain all had significant effects on the cost of production. The linear effect of BW on total costs was -$0.0704/kg. Males were less expensive to produce than females by approximately 2.5¢/kg. Strain-specific costs ranged 1.09¢/kg, with lowest cost of production in the HxR strain, and highest costs in the CxC and RxA strains. Among females and among males, the lowest cost of production was attained by the RxH and RxR strain crosses. Among males, there was greater strain separation in production costs: the RxA and CxC had the highest production costs. The cost of production range was 0.99¢/kg for females, and 1.35¢/kg for males.

### *Discussion*

***Growth models.*** One of the difficulties with the Gompertz function is the fixed point of inflection ($t^{*}=0.368*W_m$) (Darmani Kuhi et al., 2003). Biologically there is not a good reason that this point should be fixed. For situations in which growth is constrained by nutritional or environmental conditions, other models may provide a better fit. Recently, alternative flexible sigmoidal growth curves have been proposed, which are more suitable for modeling constrained growth. These include a modified Gompertz (Talpaz et al., 2000):

$$W_t = \omega W_0 \exp^{\beta - \beta \exp^{-\lambda t^{\delta}}}$$

and several alternative flexible sigmoidal growth models (Darmani Kuhi et al., 2003), including the Richards:

$$W_t = \frac{W_0 W_m}{(W_0^n + (W_m^n - W_0^n)\exp^{-\beta\ t})^{1/n}}$$

Lopez:

$$W_t = \frac{W_0 K^{\beta} + W_m t^{\beta}}{K^{\beta} + t^{\beta}}$$

and von Bertalanffy:

$$W_t = \left[ W_m^{\upsilon} - (W_m^{\upsilon} - W_0^{\upsilon}) \exp^{-\beta\ t} \right]^{1/\upsilon} ,0 \le \upsilon \le 1/3$$

where $W_t$ is live BW; $t$ is time; $W_m$ is mature BW; $W_0$ is initial BW; $\beta$, $\lambda$, $\upsilon$, $n$, $\omega$, and $\delta$ are constants; $\beta$, $\lambda$, $\delta$, $\upsilon$ *and* $\omega$ are positive; and $n \geq -1$. By providing greater flexibility, and a better fit to growth data these forms tend to reduce correlated error variance typical in longitudinal data.

Addition of extra parameters to sigmoidal models tends to reduce estimation bias, but makes them less appealing from a biological and mechanistic perspective. For unconstrained broiler growth, the point of inflection is similar to the fixed point estimated by the Gompertz model. The Gompertz model describes unconstrained growth reasonably well. Because of its biologically meaningful parameters it has been widely adopted. Since the current model deals with unconstrained growth, the Gompertz model was chosen for this application as well. As Emmans (1981) alluded, the growth model choice is somewhat arbitrary. Switching from one to another is a relatively straightforward process. The major effort in defining growth curves lies in the environmental, nutritional, and management details of the research. Once the data are collected, parameters for any growth function can be estimated and, depending on the design of the model, implemented relatively easily.

***Simulation experiments.*** Sensitivity analysis and stochastic simulation capacities of the growth model demonstrated powerful potential to evaluate the interacting effects of genotype, nutrient, and environmental effects on growth and production economics. Analysis of repeated stochastic simulation outcomes will allow decision makers to evaluate implications of nutrition and environment on economics, and exposure to risk.

Although simulation identified lowest cost bird types, the net value of the broilers for the supply chain needs to be considered in broader terms, including costs and benefits in the hatching egg and processing sectors. Optimization at the broiler level does not necessarily imply optimization for the entire supply chain.

The approach taken in the current model of stochastically simulating genetically distinct individuals is a prerequisite to answering complex questions regarding optimal nutritional and management strategies that are imposed at a flock level, but affect individuals. Conditions required for optimal flock performance may be different than those required by the average bird. Simulating at the bird level opens the door of opportunity to answer some of those questions.

### *Conclusions*

Complexities of broiler production economics are simplified using systems models. The combination of fixed and variable economic parameters with a biological growth model offer tremendous opportunities to improved insights into the economic consequences of management decisions. Sensitivity and stochastic analysis are powerful tools, offering insight of great value to decision makers. Ongoing development of strain- and sex-specific growth parameters and mechanistic improvements to nutritional and environmental aspects of the model will decrease bias and increase the value as a decision tool for production managers and nutritionists. In combination with a processing model to elucidate the value of the output of the production process in a broader context, the model also provides substantial insights to supply chain strategists.

Table 1. Parameters[1] used to estimate gain of fat, protein and ash gain.

| Ratio[2] | Sex | *A* | $\beta$ | $R^2$ |
|---|---|---|---|---|
| Fat:Total gain | F | 0.1167 | 2.28E-03 | 0.84 |
| | M | 0.0788 | 2.25E-03 | 0.89 |
| Protein:Total gain | F | 0.1726 | -4.72E-04 | 0.58 |
| | M | 0.1619 | 3.26E-05 | 0.0056 |
| Ash:Total gain | F | 0.0266 | -3.46E-05 | 0.015 |
| | M | 0.0293 | -5.56E-05 | 0.048 |

[1]Parameters for the equation $Y_t = \alpha + \beta * t$ where $Y_t$ is one of three gain ratios at age $t$ (d); and $\alpha$ and $\beta$ are least squares coefficient estimates.

[2]Gain ratios indicate the proportion of total daily gain for each component. The balance of the gain is water.

Table 2. Sensitivity to mortality of total expenses, break even income to meet cash flow needs, and margins over feed and chick costs, total costs, and all costs.

| Mortality | Total Expenses (Break even income) | Break even income for all cash outlays | Margin over feed and chick cost | Margin over total variable costs | Net return (margin over all costs) |
|---|---|---|---|---|---|
| — % — | ($/kg) | | | | |
| 0.0 | 1.0046 | 0.9785 | 0.4437 | 0.3182 | 0.1934 |
| 2.5 | 1.0127 | 0.9866 | 0.4366 | 0.3101 | 0.1853 |
| 5.0 | 1.0212 | 0.9951 | 0.4292 | 0.3016 | 0.1768 |
| 7.5 | 1.0302 | 1.0041 | 0.4213 | 0.2927 | 0.1678 |
| 10.0 | 1.0396 | 1.0135 | 0.4131 | 0.2832 | 0.1584 |
| 12.5 | 1.0496 | 1.0236 | 0.4043 | 0.2732 | 0.1484 |
| 15.0 | 1.0602 | 1.0341 | 0.3951 | 0.2626 | 0.1378 |
| 17.5 | 1.0715 | 1.0454 | 0.3852 | 0.2514 | 0.1265 |
| 20.0 | 1.0834 | 1.0573 | 0.3748 | 0.2394 | 0.1146 |
| 22.5 | 1.0961 | 1.0700 | 0.3637 | 0.2267 | 0.1019 |
| 25.0 | 1.1096 | 1.0836 | 0.3518 | 0.2132 | 0.0884 |
| 27.5 | 1.1241 | 1.0980 | 0.3392 | 0.1987 | 0.0739 |
| 30.0 | 1.1396 | 1.1136 | 0.3256 | 0.1832 | 0.0584 |
| 32.5 | 1.1563 | 1.1302 | 0.3110 | 0.1665 | 0.0417 |
| 35.0 | 1.1743 | 1.1482 | 0.2953 | 0.1486 | 0.0237 |
| 37.5 | 1.1937 | 1.1676 | 0.2784 | 0.1292 | 0.0043 |
| 40.0 | 1.2147 | 1.1886 | 0.2600 | 0.1082 | -0.0167 |
| 42.5 | 1.2375 | 1.2114 | 0.2400 | 0.0853 | -0.0395 |
| 45.0 | 1.2624 | 1.2363 | 0.2183 | 0.0604 | -0.0644 |
| 47.5 | 1.2897 | 1.2636 | 0.1944 | 0.0331 | -0.0917 |
| 50.0 | 1.3197 | 1.2936 | 0.1682 | 0.0031 | -0.1217 |

Table 3. Design and results of stochastic analysis experiment. One thousand draws from normal distributions with mean mortality of 5% and a mean FCR of 1.8. Standard deviations for mortality and FCR for each scenario are indicated. The probability of achieving an outcome where total expenses exceed $1.05 is presented for each scenario.

| Standard deviation of Mortality | Standard deviation of FCR | |
|---|---|---|
| | 0.1 | 0.2 |
| 1% | Scenario A: 14% | Scenario B: 31% |
| 2% | Scenario C: 16% | Scenario D: 29% |

Table 4. Estimates of total production costs for male and female broilers of six commercial strain crosses[1] simulated to target market BW of 1.8 to 2.9 kg.

| Effect | Sex | Strain | Total cost ($/kg live) |
|---|---|---|---|
| BW | | | -0.0704 |
| | | | |
| Sex | Female | | 0.9986[a] |
| | Male | | 0.9738[b] |
| Pooled SEM | | | 0.0006 |
| | | | |
| Strain | | PxA | 0.9875[b] |
| | | RxA | 0.9906[a] |
| | | CxC | 0.9912[a] |
| | | HxH | 0.9844[c] |
| | | RxH | 0.9803[d] |
| | | RxR | 0.9833[c] |
| Pooled SEM | | | 0.0011 |
| | | | |
| Sex* Strain | Female | PxA | 1.0018[a] |
| | | RxA | 1.0003[a] |
| | | CxC | 1.0031[a] |
| | | HxH | 0.9997[a] |
| | | RxH | 0.9933[b] |
| | | RxR | 0.9932[b] |
| | Male | PxA | 0.9732[de] |
| | | RxA | 0.9808[c] |
| | | CxC | 0.9793[c] |
| | | HxH | 0.9690[ef] |
| | | RxH | 0.9673[f] |
| | | RxR | 0.9734[d] |
| Pooled SEM | | | 0.0015 |
| | | | |
| Probability | | Prob > F | |
| BW | | <0.0001 | |
| Sex | | <0.0001 | |
| Strain | | <0.0001 | |
| Sex*Strain | | 0.0006 | |

[1]Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

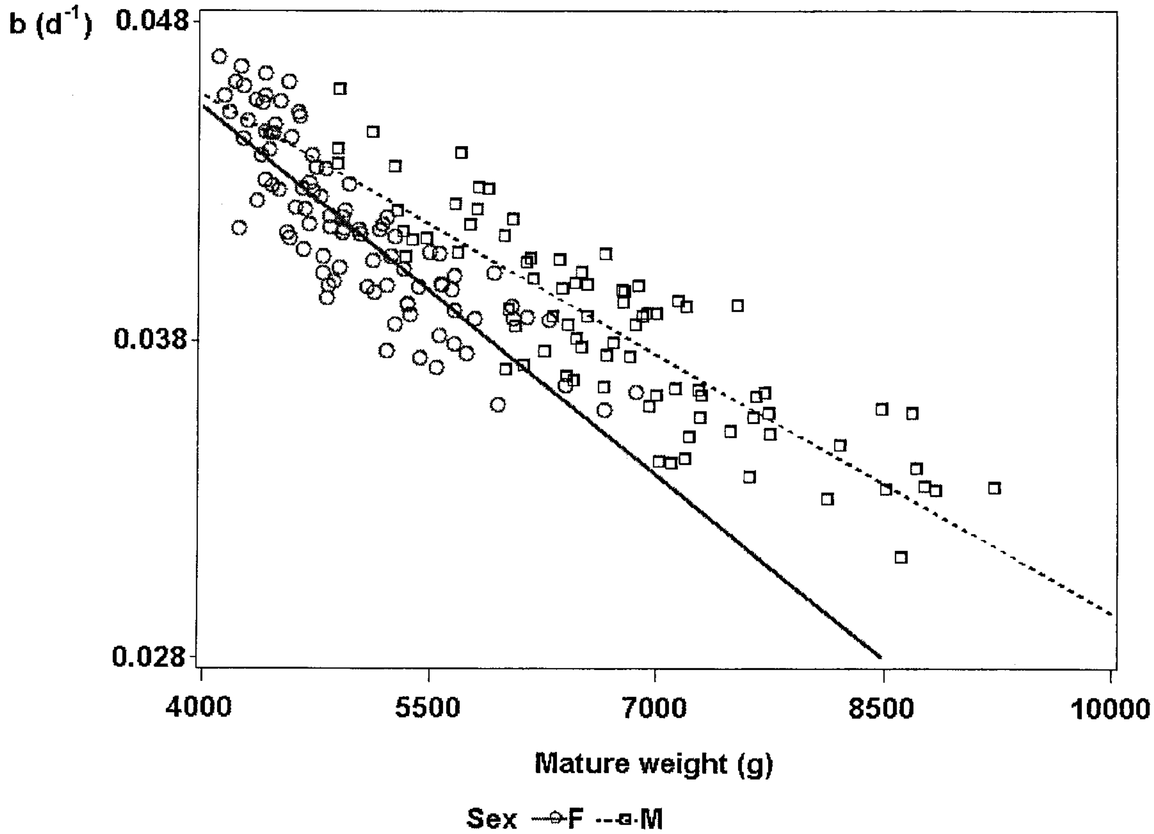


Figure 1. Contrast between males and females in the nature of the relationship of rate of maturing (*b*) with mature BW estimates. Data are from six commercial strain crosses.

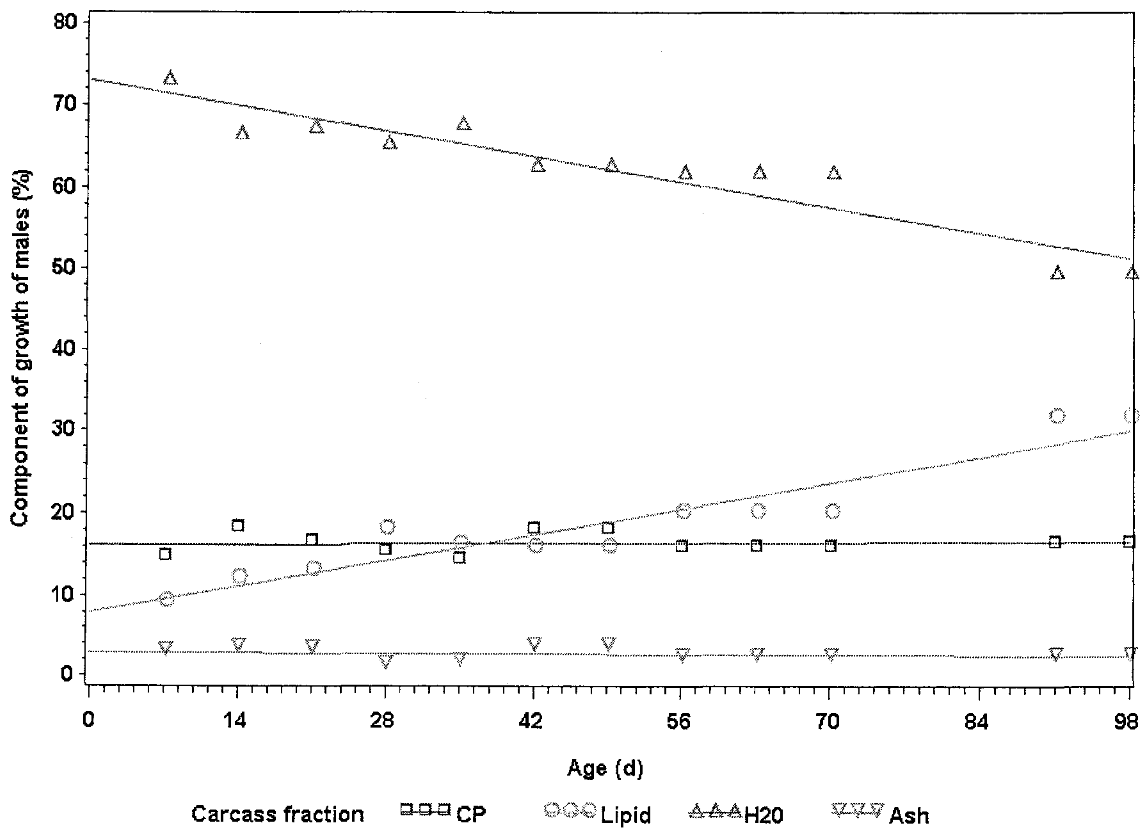


Figure 2. The chemical composition of the growth of males from 0 to 98 d of age.

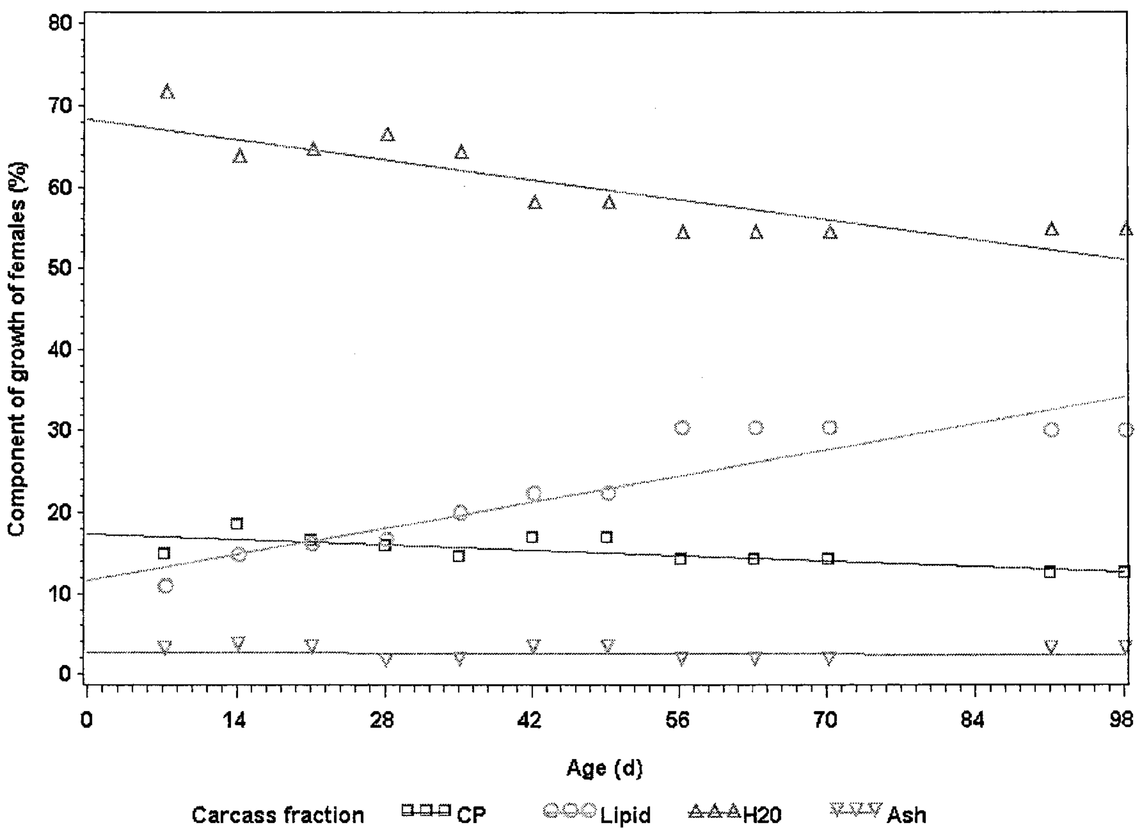


Figure 3. The chemical composition of the growth of females from 0 to 98 d of age.

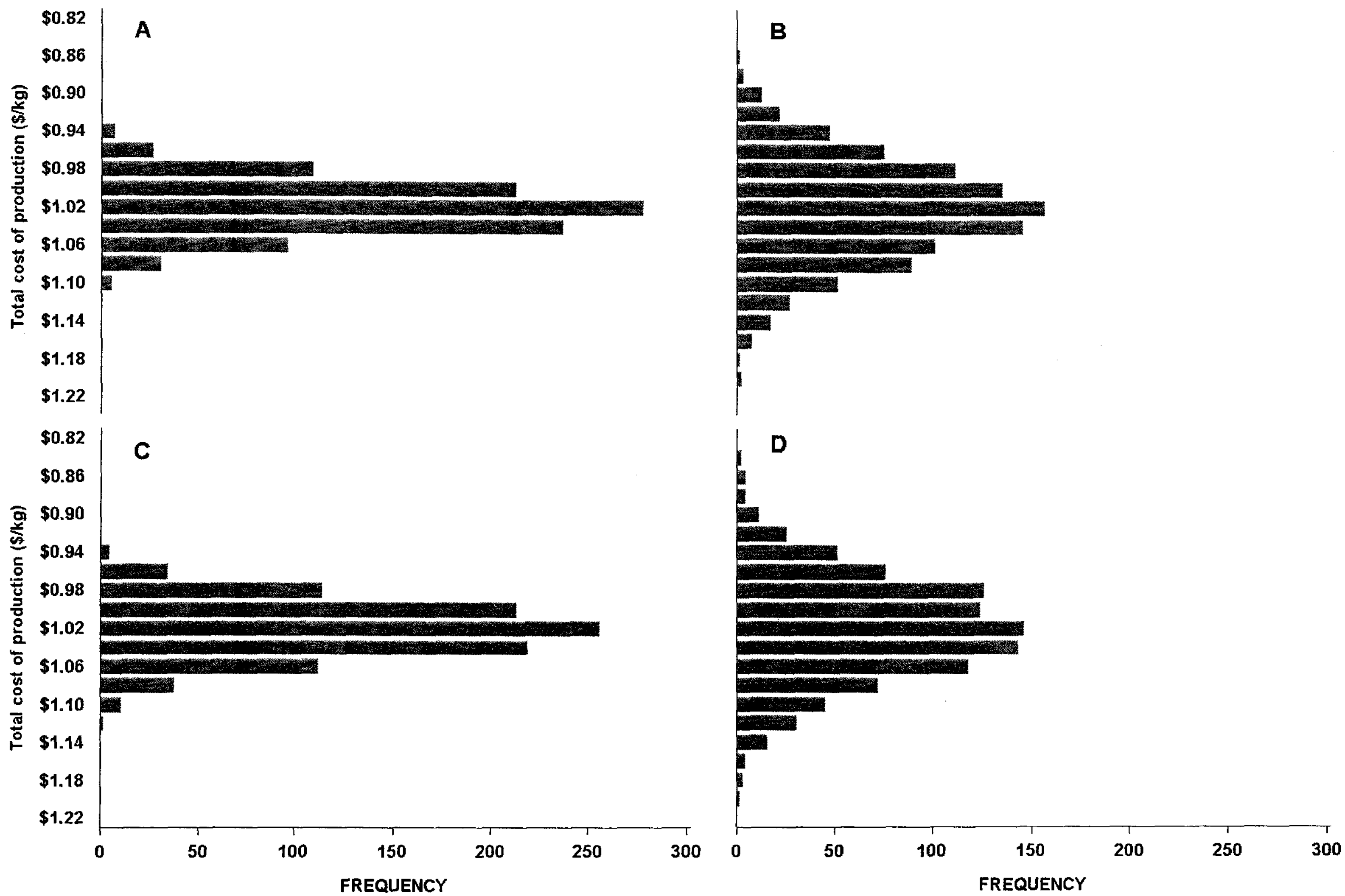


Figure 4. Outcome distributions for 1000 simulations of four broiler production scenarios, all with an average mortality rate of 5%, and a mean FCR of 1.80, and different standard deviations. Standard deviations for mortality and FCR for scenario A: 1% & 0.10; B: 1% & 0.20; C: 2% & 0.10; D: 2% & 0.20, respectively.

*References*

Buyse, J., H. Michels, J. Vloeberghs, P. Saevels, J. M. Aerts, B. Ducro, D. Berckmans, and E. Decuypere. 1998. Energy and protein metabolism between 3 and 6 weeks of age of male broiler chickens selected for growth rate or for improved food efficiency. Br. Poultry Sci. 39:264-272.

Chicken Farmers of Canada. 2003. Chicken Data Handbook. Chicken Farmers of Canada, 350 Sparks Street Suite 1007, Ottawa Ontario K1R 7S8.

Chwalibog, A. 1991. Energetics of animal production. Acta Agric. Scand. 41:147-160.

Darmani Kuhi, H., E. Kebreab, S. Lopez, and J. France. 2003. An evaluation of different growth functions for describing the profile of live weight with time (age) in meat and egg strains of chicken. Poultry Sci. 82:1536-1543.

Emmans, G. C. 1981. A model of the growth and feed intake of ad libitum fed animals, particularly poultry. Computers in Animal Production. Occasional Publication No. 5. The British Society of Animal Production, Hillyer, G. M. C. T. Whittemore R. G. Gunn, eds. Harrogate.

Emmans, G. C. 1995. Problems in modelling the growth of poultry. World's Poultry Sci. J. 51:77-89.

FAOSTAT data. 2004. Food and Agriculture Organization of the United Nations. http://apps.fao.org/; accessed August, 2004.

Gompertz, B. 1825. On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. Trans. Royal Phil. Soc. 115:513-585.

Gous, R. M., E. T. Moran Jr., H. R. Stilborn, G. D. Bradford, and G. C. Emmans. 1999.

Evaluation of the parameters needed to describe the overall growth, the chemical growth, and the growth of feathers and breast muscles of broilers. Poultry Sci. 78:812-821.

Grosskopf, K. and E. Matthaus. 1990. Mathematical simulation of the broiler production process. Syst. Anal. Model. Simul. 7:473-491.

Hancock, C. E., G. D. Bradford, G. C. Emmans, and R. M. Gous. 1995. The evaluation of the growth parameters of six strains of commercial broiler chickens. Br. Poultry Sci. 36:247-264.

Havenstein, G. B., P. R. Ferket, and M. A. Qureshi. 2003. Growth, livability, and feed conversion of 1957 versus 2001 broilers when fed representative 1957 and 2001 broiler diets. Poultry Sci. 82:1500-1508.

Hurwitz, S. 1980. Protein and amino acid requirements of poultry. Proceedings of the 3rd EAAP - Symposium on protein metabolism and nutrition, Braunschweig, F. R. Germany.

Leeson, S. and J. D. Summers. 2001. Nutrition of the Chicken. University Books, Guelph, ON.

Martin, P. A., G. D. Bradford, and R. M. Gous. 1994. A formal method of determining the dietary amino acid requirements of laying-type pullets during their growing period. Br. Poultry Sci. 35:709-724.

Narushin, V. G. and C. Takma. 2003. Sigmoid model for the evaluation of growth and production curves in laying hens. Biosyst. Eng. 84:343-348.

NRC. 1994. Nutrient Requirements of Poultry. National Research Council. National Academy Press, Washington D.C.

SAS System, Version 8.02. Copyright © 1999-2001 by SAS Institute, Inc., Cary, NC, USA.

Shalev, B. A. and H. Pasternak. 1998. The relative energy requirement of male vs female broilers and turkeys. Poultry Sci. 77:859-63.

Stilborn, H. L., E. T. Moran Jr., R. M. Gous, and M. D. Harrison. 1997. Effect of age on feather amino acid content in two broiler strain crosses and sexes. J. Appl. Poultry Res. 6:205-209.

Talpaz, H., Cohen, M., and Fancher, B. I. 2000. Ranking broiler strain cross performance in commercial complexes under varying nutrient concentrations. Proceedings of the Annual Nutrition Conference, Fayetteville, Arkansas. The Poultry Federation.

Wang, Z. and M. J. Zuidhof. 2004. Estimation of growth parameters using a nonlinear mixed gompertz model. Poultry Sci. 83:847-852.

Zoons, J., J. Buyse, and E. Decuypere. 1991. Mathematical models in broiler raising. World's Poultry Sci. J. 47:243-255.

Zuidhof, M. J. 2004. Mathematical characterization of broiler carcass yield dynamics. Poultry Sci. Submitted for publication.

Appendix 1. Base economic scenario for sensitivity analysis.

## Broiler Chicken Economic Model

**Comments**

**Strains** Ross x Ross 308

**Benchmarks**

| | | | |
|---|---|---|---|
| Placement date: 5/31/2004 | | Marketing date: 7/ 9/2004 | |
| Quota units (farm size) | 50,000 | Utilization factor (% of quota) | 99.800% |
| Quota leased in(out) (kg) | 0 | Conversion factor (kg/quota unit/wk) | 0.3700 |
| Chicks placed per cycle | 78,723 | Cycle length (wk) | 8 |
| Chicks paid for ( 2.0% free) | 77,178 | Cycles per year | 6.522 |
| Birds marketed per cycle | 73,852 | Bird age at marketing (days) | 39 |
| Live production per cycle (kg) | 147,704 | Mortality (%) | 5.0000% |
| Market weight (kg) | 2.0000 | Condemns(%) | 1.2500% |
| Live broiler price ($/kg) | 1.1980 | Chick weight (g) | 42.00 |
| Premium ($/kg) | 0.0000 | **Stocking Density** | |
| Barn space (sq ft) | 50,000 | sq ft/bird placed | 0.6351 |
| Barn cost ($/sq ft) | 11.0000 | sq ft/bird marketed | 0.6770 |
| Equipment cost ($/sq ft) | 4.3500 | kg marketed/sq ft | 2.9541 |

**Capital Costs**

| | |
|---|---|
| Land $1,000/acre | 20,000 |
| Building | 550,000 |
| Equipment | 217,500 |
| Shop | 10,000 |
| Mobile equipment | 10,000 |
| Quota $41.72/unit | 2,086,000 |
| Total Capital Costs | 2,893,500 |

**Feed Costs**

| | | Consumption (kg/bird) | $/tonne | $/bird |
|---|---|---|---|---|
| Feed conversion rate | 1.8000 | | | |
| Starter | | 0.200 | 318.00 | 0.0636 |
| Grower | | 0.400 | 281.00 | 0.1124 |
| Finisher | | 1.524 | 273.00 | 0.4162 |
| Finisher II | | 1.400 | 252.50 | 0.3535 |
| Other | | 0.000 | 252.50 | 0.0000 |
| Weighted feed cost | | | 268.32 | 0.9457 |

**Fixed Costs**

| | Annual | $/cycle | $/kg |
|---|---|---|---|
| Money borrowed: $ 80,000 ( 2.76% of investment) | | | |
| **Loan payment** | 83,176 | 12,753 | 0.0863 |
| Principal portion | 77,376 | 11,863 | 0.0803 |
| Interest portion (@7.250%) | 5,800 | 889 | 0.0060 |
| Debt servicing ratio 3.350 | | | |
| Insurance | 5,800 | 889 | 0.0060 |
| Taxes | 6,150 | 943 | 0.0064 |
| **Depreciation** | 102,500 | 15,715 | 0.1064 |
| Building (10%/yr) | 56,000 | 8,586 | 0.0581 |
| Equipment (20%/yr) | 43,500 | 6,669 | 0.0452 |
| Mobile Equipment (30%/yr) | 3,000 | 460 | 0.0031 |
| Quota ( 0.00%/yr) | 0 | 0 | 0.0000 |
| Total Fixed Costs | 120,250 | 18,437 | 0.1248 |

Printed: 8/4/2004 File: ECONOMIC SCENARIOS.CO2 BCSCM version 2.46 page 1 of 2

| Variable Costs | $/unit | $/cycle | $/kg |
|---|---|---|---|
| Chick | 0.5550 | 42,835 | 0.2900 |
| Vaccination | 0.0000 | 0 | 0.0000 |
| Sexing | 0.0000 | 0 | 0.0000 |
| Feed | 268.32 | 70,723 | 0.4788 |
| Catching (per bird caught) | 0.0601 | 4,495 | 0.0304 |
| Utilities / Energy ($ / month) | 2,300 | 4,293 | 0.0291 |
| Labour (9.15 hours/flock/day) | 12.00 | 6,149 | 0.0416 |
| Repairs (0.8635% of capital costs) | 6,800 | 1,043 | 0.0071 |
| Veterinary | | 350 | 0.0024 |
| Litter | | 375 | 0.0025 |
| ACP levy | 0.0125 | 1,846 | 0.0125 |
| Quota leased in (out) 0 kg @ 0.0000 /kg | | 0 | 0.0000 |
| Market development quota 0 kg @ 0.0000 /kg | | 0 | 0.0000 |
| Miscellaneous | | 290 | 0.0020 |
| Total Variable Costs | | 132,398 | 0.8964 |

| Summary of Costs and Returns | annual | $/cycle | $/kg |
|---|---|---|---|
| **Summary of income** | | | |
| Base income (live production) | 1,154,121 | 176,949 | 1.1980 |
| Premium | 0 | 0 | 0.0000 |
| Miscellaneous | 0 | 0 | 0.0000 |
| Total income | 1,154,121 | 176,949 | 1.1980 |
| **Summary of expenses** | | | |
| Feed and chick cost | 740,659 | 113,558 | 0.7688 |
| Other variable costs | 122,885 | 18,841 | 0.1276 |
| Total fixed costs | 120,250 | 18,437 | 0.1248 |
| Total expenses | 983,794 | 150,835 | 1.0212 |
| **Margins** | | | |
| Over feed and chick | 413,462 | 63,392 | 0.4292 |
| Over total variable costs | 290,577 | 44,551 | 0.3016 |
| Over all costs (net return) | 170,327 | 26,114 | 0.1768 |
| Cash flow (before loan principal payment) | 272,827 | 41,830 | 0.2832 |
| Cash flow (after loan principal payment) | 195,450 | 29,966 | 0.2029 |
| Break even for all cash outlays | 958,670 | 146,983 | 0.9951 |
| Break even income | | | 1.0212 |
| Gross income | | | 1.1980 |
| **Net Return** | | | |
| (per bird shipped) | | $0.3536 | |
| (per kg shipped) | | | $0.1768 |
| (per kg shipped and paid for) | | | $0.1768 |
| (per square foot) | | | $0.5223 |

Printed: 8/4/2004 File: ECONOMIC SCENARIOS.CO2 BCSCM version 2.46 page 2 of 2

# CHAPTER 5. MATHEMATICAL CHARACTERIZATION OF BROILER CARCASS YIELD DYNAMICS[1]

**ABSTRACT** Evaluation of broiler chicken supply chain economics depends on robust biological models that describe growth and yield of broiler chickens. In this paper, eight dynamic nonlinear broiler carcass and carcass part yield models were evaluated statistically for their suitability for predicting weights of carcass parts. The analysis employed four sigmoidal (S) models (Gompertz, modified Gompertz, Richards and Lopez) describing carcass part weight as a function of age, as well as three diminishing returns (DR) models (Lopez, Mitscherlich and log-linear), and a log-linear proportional yield (PY) model, which describe carcass part yield and weight, respectively, as a proportion of feather- and fat-free empty BW (FFFEBW). Three S models with a flexible point of inflection were better able to predict carcass part weights than a fixed point of inflection Gompertz model and, in general, the DR models. The log-linear models were the only models that converged in 100% of the evaluations. The PY model predicted weights for most carcass parts with the smallest degree of error and with substantially less bias than the DR log-linear model. Estimates of the coefficients for the modified Gompertz and the log-linear PY model are included for twelve key carcass parts. Estimates of carcass chemical composition are presented for the log-linear PY model.

*(Key words*: nonlinear models, carcass parts, yield, statistical evaluation, carcass composition)

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[1] A version of this chapter has been submitted to Poultry Science for publication.

**Abbreviation key**: S = sigmoidal; DR = diminishing returns; PY = proportional yield; FFFEBW = feather- and fat-free empty BW; RMSE = root mean squares error

### *Introduction*

To evaluate the economics of a dynamic system, its mechanisms must be elucidated. Comprehensive data and analysis of this subject exists in the literature (Osbaldiston, 1967). For contemporary analysis, these data are of limited use because of large changes in the genetic potential of commercial broiler strains, and the inability of quadratic functions to predict yield outside the range of BW common at that time. High performance computer hardware and statistical software make more complex, comprehensive, and robust analysis possible. Economic evaluation of the broiler chicken supply chain is limited by the scarcity of robust models describing carcass part yield.

More recently, most researchers report yield in a static manner at single or multiple points in time (Orr et al., 1984; Vieira and Moran, 1998; Peak et al., 2000; Havenstein et al., 2003). There are some nonlinear analyses with respect to nutritional inputs (Mendes et al., 1997; Kalinowski et al., 2003), and with respect to nutritional inputs and time for multiple strains over a relatively narrow time frame (Smith et al., 1998; Smith and Pesti, 1998). Few comprehensive nonlinear analyses of carcass yield over a wide range of ages or BW have been published; where they have been published, they typically describe few parameters. Breast muscle has been given particular attention (Gous et al., 1999; Scheuermann et al., 2003) because in the North American marketplace it is the most important carcass part from an economic standpoint. A recent publication describes yield curves for several important carcass components using a Richards growth function, but the yield analysis is limited to breast and leg components of males (Goliomytis et al., 2003). Although prediction of breast muscle yield is of primary importance in economic modeling, the ability to predict the weight of all carcass parts is needed to optimize production and processing decisions.

To support decisions about the selection of strains and marketing weights, an experiment was conducted to develop strain-specific mathematical descriptions of the yield of carcass parts of males and females from six commercial strain crosses representing a substantial range in commercially available broiler stocks in North America. A comparative study elucidated the nonlinear dynamics of the weights of broiler carcass parts. The primary objective of this study was to define parameters for nonlinear equations that could predict weights of many parts of the broiler carcass at any relevant processing age. A secondary objective was to statistically evaluate candidate nonlinear models for their ability to predict carcass part weights with maximal accuracy and minimal bias.

### *Materials and Methods*

#### *Stocks and Management*

The care of the birds used in this experiment met the guidelines of the Canadian Council of Animal Care (CCAC, 1993). The Faculty Animal Policy and Welfare Committee of the University of Alberta approved all protocols. A 16-wk experiment was conducted with a 6 x 2 factorial arrangement of treatments, with six Strains and two Sexes. Chicks of each Strain were selected from a single commercial broiler breeder flock. To standardize initial chick weight, parent flocks of similar age were selected (average 46 wk). Details of the strain crosses used in both studies are provided in Table 1.

All chicks were vent-sexed and identified with duplicate wing bands on the day of hatch. A total of 180 chicks (24 per treatment +25% spares) were placed into each of two replicate pens with a floor area of 9.1 $m^2$. Starter (0 to 21 d), grower (21 to 35 d), and two finisher (35 to 49 d and 49 to 112 d) diets were formulated to provide 100% of recommended energy, and 105% of recommended protein levels (NRC, 1994). Diets were formulated to ensure adequate levels of the first three amino acids most likely to be limiting – lysine, methionine + cystine, and threonine. Adequate feeder space (5 cm per bird) and water nipple availability (15 birds per water nipple) was provided. *Ad libitum* access to feed and water was provided for the duration of the trial.

***Carcass yield data***

Two birds per Strain by Sex combination (one per replicate) were randomly predetermined at hatch for dissection at 7 d intervals from 0 to 56 d, and at 14 d intervals from 56 to 112 d of age. Birds that needed to be replaced because of mortality or sexing errors were replaced with spares in a manner predetermined at hatch. After birds were killed by cervical dislocation, carcasses were plucked (dry pluck until 4 wk; scald and pluck from 5 to 16 wk of age). From 5 wk to the end of the study, feather weight was estimated by subtraction of BW after plucking from BW prior to scalding. The weights of the following organs and tissues were collected: heart; liver (without gall bladder); total digestive tract (empty, without pancreas, with 1 cm of esophagus proximal to the proventriculus; adhering fat removed from the gizzard); gizzard (empty, koilin layer removed); total gut contents; abdominal fat pad (including fat removed from the gizzard); back half (back without abdominal fat, thighs and drums with skin); drums (skinless); thighs (skinless); pectoralis major; pectoralis minor; and wings (skin on). Feather free empty body mass was recorded after each gut section was emptied by squeezing the contents. Fat- and feather-free empty BW (FFFEBW) was calculated by subtracting the fat content of the carcass from the feather free empty BW.

***Carcass Chemical Composition***

After dissection, each feather free empty carcass was individually pressure-cooked for 30 minutes and homogenized using an industrial blender. A representative sample of homogenate was collected and freeze-dried. After weighing, a representative subsample of the freeze-dried homogenate was collected and oven dried. Moisture content was determined from the weight of the freeze-dried homogenate and the oven-dried subsample. Carcass moisture was calculated from the moisture content of the samples and the original weight of the carcass, correcting for moisture addition and losses during cooking. Body chemical composition was determined as follows: fat by Mojonnier diethyl ether extraction (Mills et al., 1983); CP by measuring nitrogen content using a Kjeldhal digest; and ash by combustion in a muffle furnace for 24 h at 550 C (AFLB, 2000). Due to problems with the freeze-drier, most 42 and 56 d samples were destroyed, leaving a total of 269 usable samples.

The homogenized freeze-dried samples were scanned with a Foss NIRSystems[2] 6500 visible-NIR spectrophotometer (400 to 2500nm). NIR prediction equations were developed from the chemical analysis data, which were then used to estimate chemical composition (CP, crude fat, ash, and moisture) for the entire sample. Because the NIR

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[2] Foss NIRSystems, Inc., 12101 Tech Road, Silver Spring, MD. 20904.

spectrophotometer scanned a larger sample than that used for chemical analysis, sampling bias can be reduced using NIR predictions.

### *Specification of nonlinear models*

Eight nonlinear models were considered. Four sigmoidal (S) models, which describe the weight of parts as a function of time (age) were evaluated. Sigmoidal models provide reasonable estimates of carcass part weights, and four sigmoidal models that have been described in previous studies were evaluated. The sigmoidal models were specified as follows:

Gompertz (Emmans, 1981):

$$W_t = W_{\max} \exp^{-\exp^{-b(t-log(-log(W_0/W_{max}))/b)}} \qquad [1]$$

Modified Gompertz (Talpaz et al., 2000):

$$W_t = W_0 \exp^{b-b\exp^{-ct^d}} \qquad [2]$$

Richards (Darmani Kuhi et al., 2003):

$$W_t = \frac{W_0 W_{\max}}{\left[W_0^n + (W_{\max}^n - W_0^n)\exp^{-bt}\right]^{1/n}} \qquad [3]$$

Lopez (Lopez et al., 2000):

$$W_t = \frac{W_0 K^c + W_{\max} t^c}{K^c + t^c} \qquad [4]$$

Diminishing returns (DR) models can be used to describe the growth of carcass parts as a proportion of FFFEBW. The value of DR models compared to S models is that yield can be calculated from BW estimates. In an attempt to find a flexible diminishing returns function suited to yield data, three DR models were evaluated. They included the Lopez (Lopez et al., 2000):

$$Y = \frac{Y_0 K^c + Y_{\max} W_{ff}^c}{K^c + W_{ff}^c} \qquad [5]$$

the Mitscherlich (Peek et al., 2002):

$$Y = Y_{\max}(1 - \exp^{-b^* W_{ff} - X_0}) \qquad [6]$$

and a log-linear model (Gous et al., 1999):

$$Y = aW_{ff}^b \qquad [7]$$

Finally, a log-linear proportional yield (PY) model (Gous et al., 1999) was evaluated. From the proportional yield model, the weight of each carcass part is calculated directly from the FFFEBW. Although the carcass part weights are not directly comparable as in the DR models, the advantage of the PY model is that yield data do not need to be transformed as a function of BW. The log-linear PY model was specified after Gous et al. (1999):

$$W_t = aW_{ff}^b \qquad [8]$$

In all model specifications, $W_t$ is the carcass part weight (g) at age $t$ (d); $W_0$ is the carcass part weight (g) at hatch; $W_{max}$ is mature (asymptotic) weight (g) of each carcass part; $W_{ff}$ is FFFEBW (g); $Y$ is yield (dimensionless) relative to FFFEBW; $Y_0$ is yield (dimensionless) relative to FFFEBW at hatch; $Y_{max}$ is the asymptote of the yield curve; $X_0$ is the x-intercept; and a, b, c, d, n and K are coefficients to be estimated for each strain by sex combination.

### *Statistical analysis*

Nonlinear least squares regression was conducted for each equation using the MODEL procedure of SAS (SAS System, 2001) to describe the growth patterns of various organs and tissues of males and females of six commercial strain crosses (twelve groups). The Durbin-Watson statistic (Griffiths et al. 1993) was used to determine the degree of autocorrelation of residuals in the various nonlinear models. Root mean squares error (RMSE) values and Pearson correlation coefficients ($R^2$ values) were also used to evaluate the models. Because the DR models predict percentage yield, RMSE values for carcass part weights were calculated for the three DR models as $RMSE = \sqrt{\frac{SSE}{df_{error}}}$ where $SSE$ was the sum of squared prediction errors (g), and $df_{error}$ was the error degrees of freedom ($n$-$k$; where $n$ was the total number of observations used to estimate the non-linear parameters, and $k$ was the number of parameters estimated).

## *Results*

### *Convergence*

For all models 100% convergence was achieved for all meat parts (Table 2). The log-linear models, a relatively simple two-parameter model, converged 100% of the time for all organs and gut contents. Convergence was incomplete for other models, with the highest overall rate of non-convergence for gut contents (29%) and fatpad (26%). Improving convergence success and reducing estimation bias in broiler fatpad estimates may require more complex mechanistic models such as multiphasic models. Because of the high incidence of non-convergence in fatpad and gut contents estimation, overall convergence was also evaluated omitting these two parts (Table 2). Excluding fatpad and gut contents, convergence was 100% with the log-linear (DR and PY) and Gompertz models; followed by 99% with the Modified Gompertz; 98% with the Richards; 96% with the Lopez (S) and Mitscherlich models. The lowest rate of non-convergence (81%) was observed with the Lopez DR model.

### *Goodness of fit*

The Durbin-Watson statistic (which measures the degree of autocorrelation) the Pearson correlation coefficient, and the RMSE were used to evaluate model fitness. Fitness parameters for the three types of models must be considered carefully because the independent and dependent variables differ. In some cases, calculated values of the Durbin-Watson statistic variables were missing as a result of computational errors or calculations with missing values (SAS System, 2001).

Values of the Durbin-Watson statistic and the number of cases where autocorrelation was significant were determined for all models. Of the S models (Table 3), the Gompertz model showed the highest incidence of autocorrelation. This type of problem has been identified previously for BW data (Lopez et al., 2000), due to the inflexible point of inflection of the Gompertz model, causing weights of carcass parts to be quite seriously underestimated prior to approximately 60 d of age, and overestimated subsequently (see Figure 4). The occurrence of significant autocorrelation (Table 3) was very consistent across the three variable-point-of-inflection S models. The S models were very similar in their predictions, as is evident from Figure 4. Consistency of prediction by the S models was evident for all carcass parts. The degree of autocorrelation resulting from predictions with the log-linear PY model was similar to that of the variable inflection point S models.

Autocorrelation was more evident in the DR models, with significant autocorrelation occurring in almost two-thirds of the analyses (Table 4). When the predicted proportional yields were used to predict the weights of carcass parts, the residuals were similar in scale to the variable point of inflection S models (Figure 4), although a greater degree of autocorrelation is evident visually. On average, P. major yield tends to be underestimated prior to 35 d of age and after 77 d of age, and overestimated in the period between 35 to 77 d. This trend is consistent for all carcass parts. In general, autocorrelation is greater for females than for males, perhaps due to a more significant additional phase of growth.

RMSE values were calculated only where models converged; RMSE values may be underestimated where non-convergence occurred. RMSE are presented for the S models in Table 5, and the DR models and the PY model in Table 6. RMSE values were consistently lower in the S models compared to the DR models for all parts, with the exception of P. major, where the log-linear model had a lower RMSE (Tables 4 and 5). For P. minor estimates, RMSE from the log-linear DR model were similar to those obtained for the S models. The lowest RMSE values were obtained with the log-linear PY model in 8/12 analyses for meat parts, and 2/12 analyses of viscera weights.

The Pearson correlation coefficient cannot be compared across model types because of differences in both the dependent and independent variables (weight vs. age; proportional yield vs. FFFEBW; and weight vs. FFFEBW). Within the S models, $R^2$ values for the Gompertz were consistently lower than for the models with variable points of inflection. Correlation coefficients generated by the log-linear PY model were similar to those of the variable point of inflection S models. Among the DR models, the Mitscherlich model negative $R^2$ values in some instances, indicating that a simple mean explains more variation than the model. The Lopez DR model had relatively high $R^2$ values, but had the poorest convergence success (Table 6).

***Selection of models for parameter estimation***

Parameter estimates are presented for one S model and for the log-linear PY model. Both models provide direct estimates of part weights. The three S models with variable points of inflection (Modified Gompertz, Lopez, and Richards) all fit the carcass weight data very well. With the exception of gut contents data, the Modified Gompertz converged in every case. Therefore the Modified Gompertz model was chosen to represent the S models. The log-linear PY model converged in every case, and compared favorably with regards to the Pearson correlation coefficient and RMSE values, especially for meat parts.

***Parameter Estimates***

***Log-linear model.*** In the current study, the log-linear PY model predicts the weight of each carcass part as a function of FFFEBW. Estimates of the parameter $b$ were highly significant in every analysis. When $b$=1 in the log-linear PY model, the relationship between the carcass part weight and FFFEBW is linear. Values greater than 1 indicate that the carcass part increases in weight at a rate greater than FFFEBW; conversely, when $b$<1 the part contributes less to BW as the broiler increases in size.

Estimates of the coefficients for the log-linear PY model are presented for P. major and P. minor (Table 7). Values of $b$ for P. major and P. minor were greater than 1, indicating that breast muscle weight increases at a rate greater than the carcass as a whole. In practical terms, breast muscle yield increases as a percentage of total carcass weight as broilers get heavier. For P. major, values of $b$ ranged from 1.18 to 1.44. The average value of $b$ for males (1.32) was lower than for females (1.37). For P. minor, $b$ values ranged from 1.21 to 1.43, averaging 1.35 in males, and 1.39 in females. In practical terms, P. minor weights increased proportionally with BW more than P. major weights, and the proportion of breast muscle increased with BW more in females than in males.

Parameter estimates for back half and wings are presented in Table 8. All estimates of $a$ were significant ($P \leq 0.0554$). The back half and wings matured at about the same rate as the carcass as a whole; values of $b$ were slightly greater than 1 for the back half, averaging 1.04 for females and 1.08 for males, and slightly less than 1 for wings, averaging 0.96 overall. Estimates of $b$ for skinless and drums (Table 9) were very similar to back half $b$ estimates, while for thighs $b$ values were slightly higher at 1.12 for females, and 1.16 for males. Figure 3 illustrates graphically that breast yield continued to increase with BW whereas the back half increased quickly at first, then reached a plateau relative to FFFEBW.

Estimates of $b$ for organs were much less than 1, indicating that they matured earlier, and became less significant as a proportion of increasing BW. For the gizzard (Table 10), the mean estimate of $b$ was 0.44; 0.55 for the total gut (empty; Table 12); 0.76 for the heart; and 0.77 for the liver (Table 11). The heart and liver remain relatively metabolically active, and this was reflected in the higher $b$ parameter values. One of the functions of the liver is lipid metabolism. Fat deposition and lipid metabolism related to the deposition of yolk become more important as birds, especially females, mature. The values for $b$ for fatpad (Table 10) were the highest of all those measured, at 1.59 for females and 1.53 for males. A very high degree of variation in fatpad weights, however resulted in non-significant estimates of $a$. Visual analysis of the fatpad weight data (Figure 3) suggests a puberty-related increase in fatpad weight toward the end of the trial.

Estimates of $b$ for gut contents averaged 0.80 and 0.87 for females and males, respectively (Table 12). Accurate estimation of the weight of gut contents aids the estimation of useable broiler parts weights.

***Modified Gompertz model.*** The modified Gompertz S model estimates carcass part weight as a function of age. Estimates of the coefficients for the modified Gompertz model are presented for weights of P. major (Table 13); P. minor (Table 14); wings (Table 15); back half (Table 16); skinless thighs (Table 17); skinless drums (Table 18); gizzard (Table 19); heart (Table 20); liver (Table 21); empty gut (Table 22); fatpad (Table 23); and gut contents (Table 24).

All parameter coefficient estimates for P. major (Table 13) were significant with the exception of the $c$ coefficient for males of the RR strain, due to higher variability in P. major weights after 70 d. Similarly, all parameter coefficient estimates were significant for P. minor, back half, wings, skinless thighs, and skinless drums (Tables 13 to 17). Heart weight parameter estimates were all significant for only two strain by sex groups; liver parameter estimates for four groups. There were no cases where all coefficient estimates were significant for predicting either the weights of fatpad or gut contents.

***Carcass chemical components.*** The carcass chemical component parameters for the log-linear (PY) model are presented in Table 25. All estimates of $b$ were significant for all carcass components. Estimates of $a$ for protein and water were significant for males and females of all strains. Estimates for water were virtually linear, with an average $b$

value of 1.01 and 1.00 for females and males, respectively. Estimates for carcass protein indicate that protein content was virtually linear as well, but in females, protein content may decrease slightly with increasing weight; *b* values were 0.95 and 0.99 for females and males, respectively. For carcass lipid estimates, only one estimate of the parameter *a* was significant. This is due to substantial variation in carcass fat content, especially after approximately 2000 g of FFFEBW. For carcass lipids, estimates of *b* were all significant, and indicate increasing carcass lipid content with increasing FFFEBW. Values of *b* for carcass lipids averaged 1.38 and 1.23 for females and males, respectively. For carcass ash, all but three *a* estimates were significant. Average *b* values for ash were 0.91 and 0.94 for females and males, respectively, indicating that carcass ash content decreases with increasing FFFEBW. For carcass water, protein, lipid and ash, respectively, the Durbin-Watson statistic indicated that 92, 92, 58 and 58% of estimates showed significant autocorrelation. Where autocorrelation exists, carcass water estimates tend to be slightly overestimated for commercially relevant BW, in the 1000 to 2000 g FFFEBW range. Conversely, carcass protein, lipid, and ash estimates tend to be underestimated in this range.

## *Discussion*

### *Independent variable selection.*

Care was taken in the selection of an independent variable. As broilers age, they become heavier. Because of a high correlation between the independent variables age and BW, the choice of an independent variable for yield models is unclear. Figure 1 illustrates the degree to which BW and important carcass meat parts depend on age. Clearly there were differences in the degree of maturity in each part as a function of age. While back half and wing weights approached a plateau or asymptote by 112 d of age, the weights of P. major and P. minor muscles continued to grow at a more rapid rate, presumably accounting for much of the increase in live weight past 112 d. Figure 2 illustrates the weights of various organs and the abdominal fat pad as a function of age. Since the relative rate of growth decreases with age, the digestive organs and the weight of their contents tend to plateau early, while the growth of the heart continues longer, presumably to support increasing metabolic demands of a larger organism. A much later abdominal fat asymptote is evident from Figure 2.

Figure 3 illustrates the degree to which dark meat (back half), breast meat, and total carcass fat depend on live BW and FFFEBW. Deposition of fat is mechanistically complex. Therefore a preliminary analysis of P. major, Back half, and Wing yield was conducted using the DR log-linear model. Inferential efficiency was almost identical when using FFFEBW or live BW as the independent variable for P. major, back half and wing weights. As Emmans (1981) uses protein weight as a basis for modeling, FFFEBW was chosen as the independent variable for all analyses. Further, high accumulation of fat, especially at later ages, can lead to bias in the estimation of growth coefficients (Gous et al., 1999; Scheuermann et al., 2003).

***Allometric priorites***

With the exception of the gut and related organs, all parameters that were estimated increased proportionally with BW. Alimentary organs, represented in this analysis by gizzard and total gut weight, clearly reach an asymptote by about 49 d (see Figure 2). The liver, which is metabolically more active relative to the rest of the digestive tract, reaches a plateau later. The contribution of gut contents to total live BW plateaus more slowly than the gut itself. As the relative rate of growth decreases with age (Hancock et al., 1995), it is not surprising that the relative contribution of the gut to BW also decreases with age. This has important implications for nutrient requirements, since the gut accounts for a large proportion of total amino acid and energy requirements (McNurlan and Garlick, 1980; Cant et al., 1996).

Growth of P. major and, to an even larger degree, P. minor breast muscles continue to increase proportionally to BW. Figure 3 clearly illustrates that the breast muscles have not finished growing by 112 d of age. Back half and wings have also not achieved their mature weight, but analysis of the DR model residuals indicates that their contribution to FFFEBW is actually decreasing by 112 d of age. Fat growth, especially in females, is proportionally a substantial contributor to an increase in live BW beyond 3 kg (Figure 3).

Estimation of the growth rates of various carcass parts is important for the development of more finely tuned economic models. Nutrient requirements for maintenance and growth of different carcass parts such as meat, visceral organs, and fat, vary substantially. Knowledge of the relative growth of carcass parts will provide insights to nutritional programs. Since the composition of the broiler carcass is dynamic, more detailed simulations of growth is paramount for optimizing processing age.

***Acknowledgements***

Thanks to D. Eisenbart for excellent technical assistance and to the Alberta Agricultural Research Institute, Lilydale Poultry Company, and Alberta Chicken Producers for providing financial support for this project.

Table 1. *Experimental Design.*

| Strain | Male parent | Female parent | Parent flock age (wk) | N[A] | | |
|---|---|---|---|---|---|---|
| | | | | Males | Females | Total |
| PA | Peterson | Arbor Acres Classic | 49 | 26 | 26 | 52 |
| RA | Ross | Arbor Acres Classic | 45 | 26 | 26 | 52 |
| CC | Cobb 500 | Cobb 500 | 45 | 26 | 26 | 52 |
| HH | Hubbard | Hubbard HI-Y | 50 | 26 | 26 | 52 |
| RH | Ross | Hubbard HI-Y | 45 | 26 | 26 | 52 |
| RR | Ross | Ross 308 | 42 | 26 | 26 | 52 |
| Total | | | Average: 46 | 156 | 156 | 312 |

[A]Number in each group does not include 25% extras placed to compensate for mortality and sexing errors.

Table 2. Summary of convergence failure using eight nonlinear yield models to describe yield of broiler carcass parts.[1]

| | Sigmoidal models | | | | Diminishing returns models | | | Proportional yield model |
|---|---|---|---|---|---|---|---|---|
| | Gompertz | Modified Gompertz | Richards | Lopez | Lopez | Mitscherlich | log-linear | log-linear |
| | NC[2] | NC | NC | NC | NC | NC | NC | NC |
| P. major | - | - | - | - | - | - | - | - |
| P. minor | - | - | - | - | - | - | - | - |
| Wing | - | - | - | - | - | - | - | - |
| Back half | - | - | - | - | - | - | - | - |
| Thighs | - | - | - | - | - | - | - | - |
| Drums | - | - | - | - | - | - | - | - |
| Fatpad | - | 4 | 7 | 5 | 4 | 2 | - | - |
| Liver | - | - | 2 | 3 | 4 | - | - | - |
| Gizzard | - | - | - | - | 12 | 3 | - | - |
| Heart | - | 1 | - | 2 | 6 | 1 | - | - |
| Empty gut | - | - | - | - | 1 | 1 | - | - |
| Gut contents | 10 | 6 | 5 | 3 | - | - | - | - |
| Not converged overall | 7% | 8% | 10% | 9% | 19% | 5% | 0% | 0% |
| Convergence in all parameters except fatpad and gut contents | 100% | 99% | 98% | 96% | 81% | 96% | 100% | 100% |

[1]Males and females of six commercial strain crosses were considered as groups (n=12) that are represented in each cell in the table.

[2]No convergence: number of groups (of a total of 12) for which the least squares estimation procedure was unable to converge on a solution.

Table 3. Evaluation of the degree of autocorrelation using the Durbin-Watson statistic, using four sigmoidal models to predict carcass part yield from commercial broiler females and males.

| | | Gompertz | | Modified Gompertz | | Richards | | Lopez | |
|---|---|---|---|---|---|---|---|---|---|
| Part | Sex | DW[1] | *(%)[2] | DW | *(%) | DW | *(%) | DW | *(%) |
| P. major | F | 1.24 (0.19) | 67 | 2.19 (0.20) | 0 | 2.21 (0.19) | 0 | 2.26 (0.23) | 0 |
| | M | 1.61 (0.18) | 33 | 2.41 (0.19) | 17 | 2.41 (0.19) | 17 | 2.41 (0.19) | 17 |
| P. minor | F | 1.25 (0.18) | 67 | 2.16 (0.22) | 33 | 2.18 (0.22) | 33 | 2.18 (0.22) | 33 |
| | M | 1.54 (0.09) | 17 | 2.41 (0.09) | 0 | 2.42 (0.09) | 0 | 2.42 (0.10) | 0 |
| Wings | F | 1.26 (0.16) | 83 | 1.94 (0.16) | 17 | 1.97 (0.17) | 17 | 2.02 (0.18) | 17 |
| | M | 1.58 (0.20) | 50 | 2.27 (0.27) | 17 | 2.28 (0.27) | 17 | 2.25 (0.27) | 33 |
| Back half | F | 1.29 (0.19) | 67 | 2.14 (0.20) | 17 | 2.18 (0.19) | 0 | 2.25 (0.18) | 0 |
| | M | 1.64 (0.16) | 33 | 2.09 (0.13) | 0 | 2.11 (0.13) | 0 | 2.15 (0.12) | 0 |
| Thighs | F | 1.50 (0.17) | 50 | 2.17 (0.16) | 17 | 2.20 (0.16) | 17 | 2.23 (0.16) | 17 |
| | M | 2.08 (0.24) | 33 | 2.44 (0.15) | 33 | 2.46 (0.15) | 33 | 2.49 (0.15) | 33 |
| Drums | F | 1.53 (0.21) | 50 | 2.12 (0.25) | 33 | 2.15 (0.25) | 33 | 2.23 (0.25) | 33 |
| | M | 2.07 (0.14) | 0 | 2.47 (0.15) | 17 | 2.49 (0.15) | 17 | 2.52 (0.14) | 17 |
| Fatpad[3] | F | 2.20 (0.16) | 17 | 2.22 (0.24) | 0 | 2.89 ( . ) | 0 | 2.23 (0.17) | 17 |
| | M | 2.55 (0.24) | 50 | 2.85 (0.07) | 25 | 2.67 ( . ) | 0 | 2.65 ( . ) | 0 |
| Liver | F | 1.98 (0.27) | 17 | 2.17 (0.28) | 33 | 2.40 (0.38) | 50 | 2.13 (0.43) | 33 |
| | M | 1.97 (0.28) | 33 | 2.14 (0.31) | 50 | 2.15 (0.31) | 50 | 2.10 (0.30) | 33 |
| Gizzard | F | 1.94 (0.18) | 0 | 2.02 (0.16) | 0 | 2.02 (0.16) | 0 | 1.96 (0.12) | 0 |
| | M | 1.79 (0.13) | 0 | 2.04 (0.12) | 0 | 2.02 (0.11) | 0 | 1.99 (0.14) | 17 |
| Heart | F | 1.75 (0.27) | 33 | 1.78 (0.29) | 60 | 1.85 (0.25) | 50 | 1.86 (0.36) | 25 |
| | M | 1.67 (0.11) | 33 | 1.89 (0.13) | 17 | 1.91 (0.13) | 17 | 1.93 (0.15) | 17 |
| Empty gut | F | 1.71 (0.27) | 33 | 1.77 (0.25) | 50 | 1.76 (0.25) | 50 | 1.75 (0.22) | 33 |
| | M | 2.02 (0.23) | 17 | 2.07 (0.22) | 33 | 2.07 (0.22) | 33 | 2.01 (0.22) | 17 |
| Gut contents[3] | F | NC[4] | - | 2.49 (0.07) | 0 | NC | - | 2.48 (0.08) | 0 |
| | M | 2.09 (0.30) | 0 | NC | - | NC | - | 2.79 (0.11) | 0 |

[1]Durbin-Watson statistic mean and (standard error). Values range from 0 to 4; values close to 2 indicate non-significant autocorrelation.

[2]Percentage of converged models with significant autocorrelation

[3]Initial weight $W_t$=0, and was therefore estimated by model

[4]NC - convergence was not achieved, or calculation of the Durbin-Watson statistic was not possible, for any of the six commercial strain crosses.

Table 4. Evaluation of the degree of autocorrelation using the Durbin-Watson statistic, using three diminishing returns models and a proportional yield model to predict carcass part yield from commercial broiler females and males.

| | | Diminishing returns models | | | | | | Proportional yield model | |
|---|---|---|---|---|---|---|---|---|---|
| | | Lopez | | Mitscherlich | | log-linear | | log-linear | |
| Part | Sex | DW[1] | *(%)[2] | DW | *(%) | DW | *(%) | DW | *(%) |
| P. major | F | 1.58 (0.09) | 50 | 1.25 (0.08) | 83 | 1.50 (0.10) | 50 | 2.17 (0.13) | 0 |
| | M | 1.37 (0.15) | 67 | 1.05 (0.13) | 83 | 1.28 (0.14) | 67 | 1.97 (0.26) | 33 |
| P. minor | F | 1.58 (0.19) | 50 | 1.29 (0.15) | 83 | 1.57 (0.18) | 50 | 1.90 (0.30) | 33 |
| | M | 1.61 (0.21) | 50 | 1.28 (0.20) | 83 | 1.54 (0.17) | 50 | 1.96 (0.16) | 0 |
| Wings | F | 1.72 (0.11) | 17 | 1.71 (0.10) | 17 | 0.81 (0.10) | 100 | 1.58 (0.12) | 33 |
| | M | 1.66 (0.07) | 17 | 1.69 (0.07) | 17 | 0.69 (0.07) | 100 | 1.49 (0.09) | 17 |
| Back half | F | 1.68 (0.21) | 33 | 1.52 (0.20) | 33 | 1.44 (0.16) | 67 | 1.62 (0.26) | 50 |
| | M | 1.80 (0.11) | 33 | 1.67 (0.14) | 33 | 1.71 (0.12) | 0 | 1.91 (0.15) | 0 |
| Thighs | F | 1.84 (0.25) | 33 | 1.60 (0.21) | 33 | 1.93 (0.24) | 17 | 1.91 (0.30) | 33 |
| | M | 2.00 (0.08) | 0 | 1.80 (0.09) | 17 | 2.03 (0.08) | 0 | 2.31 (0.13) | 17 |
| Drums | F | 1.64 (0.14) | 33 | 1.63 (0.15) | 33 | 0.91 (0.09) | 100 | 1.63 (0.18) | 33 |
| | M | 1.92 (0.21) | 17 | 1.89 (0.21) | 17 | 1.47 (0.20) | 50 | 1.75 (0.27) | 33 |
| Fatpad[3] | F | 2.13 (0.39) | 33 | 1.84 (0.27) | 40 | 1.90 (0.25) | 33 | 1.99 (0.28) | 50 |
| | M | 2.13 (0.20) | 0 | 2.04 (0.23) | 20 | 1.85 (0.17) | 0 | 2.33 (0.15) | 17 |
| Liver | F | NC[4] | - | 0.39 (0.28) | 100 | 1.10 (0.10) | 83 | 1.91 (0.29) | 33 |
| | M | 0.72 (0.06) | 100 | NC | - | 1.05 (0.11) | 100 | 1.79 (0.23) | 50 |
| Gizzard | F | NC | - | 0.15 (0.03) | 100 | 1.18 (0.17) | 83 | 1.73 (0.13) | 17 |
| | M | NC | - | 0.20 (0.03) | 100 | 1.08 (0.11) | 100 | 1.78 (0.14) | 17 |
| Heart | F | 1.75 (0.28) | 50 | 0.16 ( . ) | 100 | 1.56 (0.13) | 33 | 1.79 (0.17) | 17 |
| | M | 1.96 (0.23) | 25 | NC | - | 1.52 (0.12) | 50 | 1.90 (0.22) | 33 |
| Empty gut | F | 1.01 (0.07) | 100 | 0.17 (0.01) | 100 | 0.92 (0.04) | 100 | 1.30 (0.18) | 83 |
| | M | 1.03 (0.12) | 100 | 0.27 (0.03) | 100 | 1.09 (0.12) | 83 | 1.72 (0.20) | 33 |
| Gut contents[3] | F | 2.02 (0.14) | 0 | 2.04 (0.13) | 0 | 1.38 (0.15) | 50 | 2.22 (0.12) | 0 |
| | M | 1.60 (0.22) | 17 | 1.63 (0.22) | 33 | 1.28 (0.16) | 67 | 2.12 (0.17) | 0 |

[1]Durbin-Watson statistic mean (standard error). Values range from 0 to 4; values close to 2 indicate non-significant autocorrelation.

[2]Percentage of converged models with significant autocorrelation

[3]Initial weight $W_t$=0, and was therefore estimated by model

[4]NC - convergence was not achieved, or calculation of the Durbin-Watson statistic was not possible, for any of the six commercial strain crosses.

Table 5. Evaluation of the fitness of four nonlinear sigmoidal models used to predict carcass part yield from broiler males and females. Indicators of fitness include convergence, the Pearson correlation coefficient ($R^2$)[1], and the Root Mean Squares Error (RMSE).[2]

| | | Gompertz | | | | Modified Gompertz | | | | Richards | | | | Lopez | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Part | Sex | C[3] | $R^2$ | RMSE | df | C | $R^2$ | RMSE | df | C | $R^2$ | RMSE | df | C | $R^2$ | RMSE | df |
| P. major | F | 6 | 0.961 (0.007) | 66.1 (8.3) | 21 | 6 | 0.980 (0.004) | 48.0 (6.1) | 20 | 6 | 0.981 (0.004) | 47.8 (6.1) | 20 | 6 | 0.981 (0.004) | 47.8 (6.0) | 20 |
| | M | 6 | 0.975 (0.004) | 66.7 (7.8) | 20 | 6 | 0.982 (0.004) | 57.2 (9.1) | 19 | 6 | 0.982 (0.004) | 57.1 (9.1) | 19 | 6 | 0.982 (0.004) | 57.2 (9.1) | 19 |
| P. minor | F | 6 | 0.972 (0.004) | 14.7 (1.5) | 21 | 6 | 0.987 (0.002) | 10.3 (1.0) | 20 | 6 | 0.987 (0.002) | 10.3 (1.0) | 20 | 6 | 0.987 (0.002) | 10.3 (1.0) | 20 |
| | M | 6 | 0.982 (0.002) | 14.4 (1.2) | 20 | 6 | 0.990 (0.002) | 11.1 (1.1) | 19 | 6 | 0.990 (0.002) | 11.1 (1.1) | 19 | 6 | 0.990 (0.002) | 11.1 (1.1) | 19 |
| Wings | F | 6 | 0.986 (0.003) | 15.9 (1.7) | 21 | 6 | 0.992 (0.002) | 12.5 (1.6) | 20 | 6 | 0.992 (0.002) | 12.4 (1.6) | 20 | 6 | 0.992 (0.002) | 12.2 (1.6) | 20 |
| | M | 6 | 0.993 (0.001) | 15.3 (1.4) | 20 | 6 | 0.995 (0.001) | 13.0 (1.2) | 19 | 6 | 0.995 (0.001) | 12.9 (1.1) | 19 | 6 | 0.995 (0.001) | 13.1 (1.1) | 19 |
| Back half | F | 6 | 0.986 (0.002) | 59.3 (5.5) | 21 | 6 | 0.992 (0.001) | 45.8 (5.3) | 20 | 6 | 0.992 (0.001) | 45.4 (5.3) | 20 | 6 | 0.992 (0.001) | 44.7 (5.2) | 20 |
| | M | 6 | 0.990 (0.001) | 71.9 (5.7) | 20 | 6 | 0.993 (0.001) | 64.1 (3.9) | 19 | 6 | 0.993 (0.001) | 63.8 (3.9) | 19 | 6 | 0.993 (0.001) | 63.5 (3.7) | 19 |
| Thighs | F | 6 | 0.977 (0.005) | 31.6 (4.2) | 21 | 6 | 0.985 (0.003) | 25.7 (3.6) | 20 | 6 | 0.986 (0.003) | 25.5 (3.6) | 20 | 6 | 0.986 (0.003) | 25.4 (3.5) | 20 |
| | M | 6 | 0.984 (0.003) | 38.7 (4.2) | 20 | 6 | 0.987 (0.002) | 35.9 (3.2) | 19 | 6 | 0.987 (0.002) | 35.8 (3.2) | 19 | 6 | 0.987 (0.002) | 35.8 (3.1) | 19 |
| Drums | F | 6 | 0.985 (0.002) | 18.9 (1.3) | 21 | 6 | 0.990 (0.002) | 16.0 (1.4) | 20 | 6 | 0.990 (0.002) | 15.9 (1.4) | 20 | 6 | 0.990 (0.002) | 15.6 (1.4) | 20 |
| | M | 6 | 0.988 (0.003) | 26.0 (3.9) | 20 | 6 | 0.990 (0.003) | 24.3 (3.6) | 19 | 6 | 0.990 (0.003) | 24.3 (3.6) | 19 | 6 | 0.990 (0.003) | 24.3 (3.5) | 19 |
| Fatpad[4] | F | 6 | 0.917 (0.013) | 33.1 (3.3) | 20 | 4 | 0.917 (0.019) | 34.1 (3.5) | 19 | 4 | 0.919 (0.015) | 33.4 (2.5) | 19 | 6 | 0.917 (0.013) | 33.9 (3.5) | 19 |
| | M | 6 | 0.905 (0.035) | 25.8 (4.3) | 19 | 4 | 0.875 (0.047) | 30.6 (5.4) | 18 | 1 | 0.742 ( . ) | 45.1 ( . ) | 18 | 1 | 0.742 ( . ) | 45.2 ( . ) | 18 |
| Liver | F | 6 | 0.906 (0.028) | 9.5 (1.7) | 21 | 6 | 0.913 (0.026) | 9.4 (1.7) | 20 | 4 | 0.949 (0.010) | 6.9 (0.7) | 19 | 3 | 0.955 (0.010) | 6.4 (0.7) | 19 |
| | M | 6 | 0.942 (0.011) | 10.7 (1.2) | 20 | 6 | 0.949 (0.010) | 10.3 (1.1) | 19 | 6 | 0.949 (0.010) | 10.3 (1.1) | 19 | 6 | 0.947 (0.010) | 10.4 (1.1) | 19 |
| Gizzard | F | 6 | 0.902 (0.016) | 3.7 (0.4) | 21 | 6 | 0.907 (0.017) | 3.7 (0.4) | 20 | 6 | 0.907 (0.017) | 3.7 (0.4) | 20 | 6 | 0.904 (0.017) | 3.7 (0.4) | 20 |
| | M | 6 | 0.893 (0.011) | 4.8 (0.3) | 20 | 6 | 0.905 (0.012) | 4.6 (0.4) | 19 | 6 | 0.905 (0.012) | 4.6 (0.4) | 19 | 6 | 0.898 (0.014) | 4.7 (0.4) | 19 |
| Heart | F | 6 | 0.880 (0.015) | 2.3 (0.2) | 21 | 5 | 0.896 (0.013) | 2.1 (0.2) | 20 | 6 | 0.893 (0.011) | 2.2 (0.2) | 20 | 4 | 0.903 (0.014) | 2.1 (0.2) | 20 |
| | M | 6 | 0.926 (0.014) | 2.8 (0.4) | 20 | 6 | 0.934 (0.014) | 2.7 (0.4) | 19 | 6 | 0.934 (0.014) | 2.7 (0.4) | 19 | 6 | 0.934 (0.015) | 2.7 (0.4) | 19 |
| Empty gut | F | 6 | 0.943 (0.008) | 12.1 (1.0) | 21 | 6 | 0.945 (0.009) | 12.1 (1.2) | 20 | 6 | 0.945 (0.009) | 12.1 (1.2) | 20 | 6 | 0.944 (0.009) | 12.3 (1.2) | 20 |
| | M | 6 | 0.916 (0.019) | 20.2 (2.9) | 20 | 6 | 0.920 (0.017) | 20.1 (2.8) | 19 | 6 | 0.920 (0.017) | 20.1 (2.8) | 19 | 6 | 0.915 (0.016) | 20.8 (2.7) | 19 |
| Gut contents[4] | F | 0 | NC[5] | NC | | 6 | 0.934 (0.018) | 13.9 (2.1) | 19 | 6 | 0.931 (0.015) | 14.4 (1.8) | 19 | 6 | 0.932 (0.019) | 14.1 (2.2) | 19 |
| | M | 2 | 0.899 (0.040) | 22.0 (9.7) | 19 | 0 | NC | NC | | 1 | 0.782 ( . ) | 40.6 ( . ) | 18 | 3 | 0.925 (0.034) | 17.7 (7.6) | 19 |

[1]Average Pearson correlation coefficient (standard error) for six strains

[2]Root Mean Square Error (standard error) for six strains calculated as $RMSE = \sqrt{\frac{SSE}{df_{error}}}$ where *SSE* is total sums of squared errors; $df_{error}$ is the degrees of freedom for the error term.

[3]number converged out of six per sex per carcass part

[4]Initial weight $W_t$=0, and was therefore estimated by model

[5]NC - convergence was not achieved for any of the six commercial strain crosses

Table 6. Evaluation of the fitness of three nonlinear diminishing returns models and a proportional yield model used to predict carcass part yield from broiler males and females. Indicators of fitness include convergence, the Pearson correlation coefficient ($R^2$)[1], and the Root Mean Squares Error (RMSE).[2]

| | | DR models | | | | | | | | | | | | Proportional yield model | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Lopez | | | | Mitscherlich | | | | log-linear | | | | log-linear | | | |
| Part | Sex | C[3] | $R^2$ | RMSE | df | C | $R^2$ | RMSE | df | C | $R^2$ | RMSE | df | C | $R^2$ | RMSE | df |
| P. major | F | 6 | 0.923 (0.013) | 47.1 (8.6) | 20 | 6 | 0.894 (0.014) | 50.5 (9.1) | 20 | 6 | 0.919 (0.013) | 44.9 (8.0) | 21 | 6 | 0.981 (0.006) | 44.5 (8.1) | 21 |
| | M | 6 | 0.920 (0.010) | 59.0 (5.7) | 19 | 6 | 0.884 (0.015) | 66.9 (7.5) | 19 | 6 | 0.909 (0.012) | 55.0 (6.1) | 20 | 6 | 0.985 (0.002) | 52.8 (5.1) | 20 |
| P. minor | F | 6 | 0.940 (0.004) | 9.8 (0.9) | 20 | 6 | 0.922 (0.004) | 10.3 (0.8) | 20 | 6 | 0.940 (0.005) | 9.5 (0.9) | 21 | 6 | 0.988 (0.002) | 9.4 (0.9) | 21 |
| | M | 6 | 0.919 (0.012) | 13.6 (1.6) | 19 | 6 | 0.892 (0.010) | 15.4 (1.4) | 19 | 6 | 0.913 (0.015) | 13.2 (1.6) | 20 | 6 | 0.985 (0.004) | 12.7 (1.6) | 20 |
| Wings | F | 6 | 0.870 (0.019) | 16.0 (1.5) | 20 | 6 | 0.872 (0.018) | 16.0 (1.5) | 20 | 6 | 0.645 (0.039) | 21.7 (1.5) | 21 | 6 | 0.989 (0.002) | 14.6 (1.4) | 21 |
| | M | 6 | 0.881 (0.015) | 18.5 (1.2) | 19 | 6 | 0.885 (0.015) | 18.6 (1.2) | 19 | 6 | 0.625 (0.033) | 25.6 (1.7) | 20 | 6 | 0.991 (0.001) | 17.2 (1.1) | 20 |
| Back half | F | 6 | 0.840 (0.020) | 40.0 (3.5) | 20 | 6 | 0.814 (0.020) | 40.2 (3.7) | 20 | 6 | 0.814 (0.025) | 45.4 (3.4) | 21 | 6 | 0.994 (0.001) | 39.6 (3.3) | 21 |
| | M | 6 | 0.836 (0.023) | 65.0 (8.4) | 19 | 6 | 0.817 (0.025) | 67.4 (8.1) | 19 | 6 | 0.831 (0.018) | 65.5 (8.1) | 20 | 6 | 0.993 (0.002) | 62.7 (8.2) | 20 |
| Thighs | F | 6 | 0.902 (0.011) | 21.7 (2.5) | 20 | 6 | 0.885 (0.014) | 22.0 (2.7) | 20 | 6 | 0.904 (0.013) | 21.7 (2.2) | 21 | 6 | 0.989 (0.002) | 21.3 (2.3) | 21 |
| | M | 6 | 0.877 (0.012) | 36.6 (3.6) | 19 | 6 | 0.858 (0.015) | 37.4 (3.9) | 19 | 6 | 0.882 (0.009) | 36.5 (3.2) | 20 | 6 | 0.987 (0.002) | 35.6 (3.3) | 20 |
| Drums | F | 6 | 0.801 (0.023) | 17.6 (1.8) | 20 | 6 | 0.804 (0.022) | 17.6 (1.8) | 20 | 6 | 0.588 (0.053) | 22.4 (2.2) | 21 | 6 | 0.990 (0.002) | 15.1 (1.3) | 21 |
| | M | 6 | 0.814 (0.047) | 27.0 (5.2) | 19 | 6 | 0.810 (0.049) | 27.2 (5.4) | 19 | 6 | 0.750 (0.035) | 30.1 (4.1) | 20 | 6 | 0.987 (0.005) | 25.8 (5.1) | 20 |
| Fatpad | F | 3 | 0.847 (0.056) | 30.2 (8.5) | 20 | 5 | 0.812 (0.043) | 36.3 (6.0) | 20 | 6 | 0.815 (0.039) | 35.5 (5.0) | 21 | 6 | 0.901 (0.025) | 34.6 (4.9) | 21 |
| | M | 5 | 0.784 (0.055) | 28.7 (4.9) | 19 | 5 | 0.771 (0.054) | 29.5 (4.5) | 19 | 6 | 0.758 (0.047) | 30.0 (4.6) | 20 | 6 | 0.883 (0.036) | 28.7 (4.4) | 20 |
| Liver | F | 4 | -.000 (0.000) | 14.4 (1.3) | 20 | 6 | -1.52 (1.552) | 20.6 (6.3) | 20 | 6 | 0.153 (0.036) | 10.4 (1.4) | 21 | 6 | 0.922 (0.028) | 8.5 (1.7) | 21 |
| | M | 4 | 0.157 (0.093) | 21.6 (6.9) | 20 | 6 | -.000 (0.000) | 32.5 (1.0) | 19 | 6 | 0.351 (0.042) | 18.4 (1.2) | 20 | 6 | 0.938 (0.011) | 11.0 (1.0) | 20 |
| Gizzard | F | 0 | NC[3] | NC | | 3 | 0.000 (0.000) | 32.2 (0.4) | 20 | 6 | 0.833 (0.028) | 9.2 (0.4) | 21 | 6 | 0.893 (0.017) | 3.8 (0.4) | 21 |
| | M | 0 | NC | NC | | 6 | -.000 (0.000) | 49.9 (1.6) | 19 | 6 | 0.788 (0.023) | 13.9 (0.6) | 20 | 6 | 0.887 (0.017) | 4.9 (0.5) | 20 |
| Heart | F | 2 | 0.651 (0.078) | 2.4 (0.1) | 20 | 5 | -1.52 (1.519) | 5.4 (1.4) | 20 | 6 | 0.528 (0.074) | 2.4 (0.1) | 21 | 6 | 0.896 (0.005) | 2.1 (0.1) | 21 |
| | M | 4 | 0.616 (0.091) | 2.7 (0.7) | 20 | 6 | -.000 (0.000) | 5.2 (0.3) | 19 | 6 | 0.525 (0.048) | 3.1 (0.3) | 20 | 6 | 0.931 (0.017) | 2.7 (0.5) | 20 |
| Empty gut | F | 6 | 0.804 (0.042) | 13.0 (1.1) | 20 | 5 | -.659 (0.659) | 84.4 (5.2) | 20 | 6 | 0.678 (0.030) | 31.4 (2.0) | 21 | 6 | 0.932 (0.013) | 13.1 (1.6) | 21 |
| | M | 5 | 0.686 (0.039) | 25.6 (3.2) | 19 | 6 | 0.000 (0.000) | 113 (1.9) | 19 | 6 | 0.654 (0.027) | 42.7 (1.3) | 20 | 6 | 0.902 (0.017) | 21.9 (2.6) | 20 |
| Gut contents | F | 6 | 0.778 (0.038) | 22.5 (2.8) | 20 | 6 | 0.777 (0.037) | 22.6 (2.8) | 20 | 6 | 0.329 (0.012) | 30.8 (3.1) | 21 | 6 | 0.912 (0.029) | 14.8 (2.8) | 21 |
| | M | 6 | 0.698 (0.034) | 40.3 (2.7) | 19 | 6 | 0.696 (0.035) | 40.3 (2.7) | 19 | 6 | 0.261 (0.060) | 42.2 (3.0) | 20 | 6 | 0.897 (0.022) | 23.5 (5.8) | 20 |

[1]Average Pearson correlation coefficient (standard error) for six strains

[2]Average Root Mean Squares Error (standard error) for six strains calculated as $RMSE = \sqrt{\frac{SSE}{df_{error}}}$ where $SSE$ is total sums of squared errors; $df_{error}$ is the degrees of freedom for the error term.

[3]Number out of six commercial strain crosses where the model successfully converged.

[4]NC - convergence was not achieved for any of the six commercial strain crosses

Table 7. Log-linear regression coefficients[1] for P. major and P. minor breast muscles of females and males of six commercial strain crosses[2].

| | | P. major | | | | | | | | P. minor | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sex | Strain | a | SEM | df | P | b | SEM | df | P | a | SEM | df | P | b | SEM | df | P |
| F | PA | 0.0154 | 0.0108 | 20 | 0.1691 | 1.3256 | 0.0883 | 20 | <.0001 | 0.0025 | 0.0015 | 20 | 0.1166 | 1.3911 | 0.0768 | 20 | <.0001 |
| | RA | 0.007 | 0.008 | 21 | 0.3913 | 1.4369 | 0.1411 | 21 | <.0001 | 0.0019 | 0.0012 | 21 | 0.1220 | 1.4228 | 0.0767 | 21 | <.0001 |
| | CC | 0.0114 | 0.0044 | 20 | 0.0187 | 1.3755 | 0.0484 | 20 | <.0001 | 0.0033 | 0.0019 | 20 | 0.0998 | 1.3531 | 0.0717 | 20 | <.0001 |
| | HH | 0.0111 | 0.0055 | 21 | 0.0560 | 1.3768 | 0.0616 | 21 | <.0001 | 0.0033 | 0.0011 | 21 | 0.0089 | 1.3656 | 0.0433 | 21 | <.0001 |
| | HR | 0.0144 | 0.0057 | 21 | 0.0197 | 1.3455 | 0.0491 | 21 | <.0001 | 0.0014 | 0.0005 | 21 | 0.0082 | 1.473 | 0.0424 | 21 | <.0001 |
| | RR | 0.0134 | 0.0078 | 20 | 0.1017 | 1.3459 | 0.0719 | 20 | <.0001 | 0.0036 | 0.0019 | 20 | 0.0715 | 1.3459 | 0.0648 | 20 | <.0001 |
| M | PA | 0.0086 | 0.0048 | 20 | 0.0903 | 1.3798 | 0.068 | 20 | <.0001 | 0.0016 | 0.0016 | 20 | 0.3253 | 1.4322 | 0.1199 | 20 | <.0001 |
| | RA | 0.008 | 0.0044 | 22 | 0.0783 | 1.3887 | 0.0644 | 22 | <.0001 | 0.0084 | 0.0044 | 22 | 0.0661 | 1.2104 | 0.0617 | 22 | <.0001 |
| | CC | 0.0114 | 0.0054 | 20 | 0.0477 | 1.3472 | 0.0566 | 20 | <.0001 | 0.0027 | 0.0009 | 20 | 0.0049 | 1.3519 | 0.0378 | 20 | <.0001 |
| | HH | 0.0476 | 0.032 | 20 | 0.1525 | 1.1817 | 0.0804 | 20 | <.0001 | 0.0072 | 0.0038 | 20 | 0.0736 | 1.2388 | 0.0633 | 20 | <.0001 |
| | HR | 0.024 | 0.0146 | 20 | 0.1148 | 1.2688 | 0.0727 | 20 | <.0001 | 0.0015 | 0.0011 | 20 | 0.1797 | 1.4331 | 0.086 | 20 | <.0001 |
| | RR | 0.0093 | 0.0073 | 20 | 0.2219 | 1.3759 | 0.0946 | 20 | <.0001 | 0.0013 | 0.0007 | 20 | 0.0938 | 1.4478 | 0.0677 | 20 | <.0001 |

[1] Coefficients for log-linear model $W_t = aW_{ff}^{b}$ where $W_t$ is yield as a proportion of feather- and fat-free empty BW; $W_{ff}$ is feather- and fat-free empty BW; *a* and *b* are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 8.Log-linear regression coefficients[1] for back half and wings of females and males of six commercial strain crosses[2].

| | | Back half | | | | | | | | Wings | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sex | Strain | a | SEM | df | P | b | SEM | df | P | a | SEM | df | P | b | SEM | df | P |
| F | PA | 0.1877 | 0.0499 | 20 | 0.0012 | 1.0888 | 0.0337 | 20 | <.0001 | 0.0971 | 0.0213 | 20 | 0.0002 | 1.015 | 0.0278 | 20 | <.0001 |
| | RA | 0.2989 | 0.1002 | 21 | 0.0071 | 1.0212 | 0.0417 | 21 | <.0001 | 0.2239 | 0.067 | 21 | 0.0031 | 0.8949 | 0.0374 | 21 | <.0001 |
| | CC | 0.3657 | 0.0922 | 20 | 0.0008 | 1.001 | 0.0315 | 20 | <.0001 | 0.1546 | 0.0441 | 20 | 0.0022 | 0.9454 | 0.0357 | 20 | <.0001 |
| | HH | 0.2447 | 0.0647 | 21 | 0.0011 | 1.0518 | 0.0332 | 21 | <.0001 | 0.1486 | 0.053 | 21 | 0.0106 | 0.9546 | 0.045 | 21 | <.0001 |
| | HR | 0.2932 | 0.0503 | 21 | <.0001 | 1.0283 | 0.0214 | 21 | <.0001 | 0.1139 | 0.0487 | 21 | 0.0294 | 0.9832 | 0.0535 | 21 | <.0001 |
| | RR | 0.2902 | 0.0712 | 20 | 0.0006 | 1.0305 | 0.0304 | 20 | <.0001 | 0.1698 | 0.0511 | 20 | 0.0034 | 0.9371 | 0.0375 | 20 | <.0001 |
| M | PA | 0.166 | 0.0395 | 20 | 0.0004 | 1.1048 | 0.0289 | 20 | <.0001 | 0.0991 | 0.0265 | 20 | 0.0013 | 1.0048 | 0.0326 | 20 | <.0001 |
| | RA | 0.333 | 0.0971 | 22 | 0.0024 | 1.0149 | 0.035 | 22 | <.0001 | 0.1489 | 0.0414 | 22 | 0.0016 | 0.949 | 0.0334 | 22 | <.0001 |
| | CC | 0.186 | 0.0566 | 20 | 0.0037 | 1.0874 | 0.0365 | 20 | <.0001 | 0.1716 | 0.0606 | 20 | 0.0103 | 0.9331 | 0.0426 | 20 | <.0001 |
| | HH | 0.175 | 0.086 | 20 | 0.0554 | 1.097 | 0.0589 | 20 | <.0001 | 0.1228 | 0.0429 | 20 | 0.0096 | 0.9738 | 0.042 | 20 | <.0001 |
| | HR | 0.2737 | 0.0703 | 20 | 0.0009 | 1.0405 | 0.0309 | 20 | <.0001 | 0.1309 | 0.0367 | 20 | 0.0020 | 0.9625 | 0.0339 | 20 | <.0001 |
| | RR | 0.141 | 0.0474 | 20 | 0.0075 | 1.1199 | 0.0403 | 20 | <.0001 | 0.1051 | 0.034 | 20 | 0.0058 | 0.9922 | 0.0389 | 20 | <.0001 |

[1] Coefficients for log-linear model $W_t = aW_{ff}^{b}$ where $W_t$ is yield as a proportion of feather- and fat-free empty BW; $W_{ff}$ is feather- and fat-free empty BW; $a$ and $b$ are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 9. Log-linear regression coefficients[1] for skinless thighs and drums of females and males of six commercial strain crosses[2].

| | | Thighs (skinless) | | | | | | | | Drums (skinless) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sex | Strain | a | SEM | df | P | b | SEM | df | P | a | SEM | df | P | b | SEM | df | P |
| F | PA | 0.0766 | 0.0292 | 20 | 0.0162 | 1.0798 | 0.0482 | 20 | <.0001 | 0.1006 | 0.0237 | 20 | 0.0004 | 1.022 | 0.0298 | 20 | <.0001 |
| | RA | 0.049 | 0.0266 | 21 | 0.0791 | 1.1346 | 0.0673 | 21 | <.0001 | 0.233 | 0.0879 | 21 | 0.0150 | 0.9064 | 0.0471 | 21 | <.0001 |
| | CC | 0.0595 | 0.0236 | 20 | 0.0203 | 1.119 | 0.0494 | 20 | <.0001 | 0.1827 | 0.0546 | 20 | 0.0032 | 0.9407 | 0.0374 | 20 | <.0001 |
| | HH | 0.0421 | 0.0134 | 21 | 0.0050 | 1.1596 | 0.0399 | 21 | <.0001 | 0.2269 | 0.0584 | 21 | 0.0009 | 0.9105 | 0.0325 | 21 | <.0001 |
| | HR | 0.0543 | 0.014 | 21 | 0.0008 | 1.1274 | 0.032 | 21 | <.0001 | 0.2428 | 0.0742 | 21 | 0.0036 | 0.9049 | 0.0383 | 21 | <.0001 |
| | RR | 0.0546 | 0.0168 | 20 | 0.0040 | 1.1266 | 0.0381 | 20 | <.0001 | 0.146 | 0.0365 | 20 | 0.0007 | 0.9717 | 0.0311 | 20 | <.0001 |
| M | PA | 0.042 | 0.0213 | 20 | 0.0630 | 1.1605 | 0.0617 | 20 | <.0001 | 0.099 | 0.0345 | 20 | 0.0095 | 1.0331 | 0.0425 | 20 | <.0001 |
| | RA | 0.0816 | 0.0254 | 22 | 0.0040 | 1.0752 | 0.0373 | 22 | <.0001 | 0.1558 | 0.0292 | 22 | <.0001 | 0.9712 | 0.0225 | 22 | <.0001 |
| | CC | 0.0276 | 0.0154 | 20 | 0.0891 | 1.2121 | 0.067 | 20 | <.0001 | 0.1347 | 0.0636 | 20 | 0.0471 | 0.9932 | 0.0569 | 20 | <.0001 |
| | HH | 0.031 | 0.0189 | 20 | 0.1175 | 1.1984 | 0.0731 | 20 | <.0001 | 0.0817 | 0.055 | 20 | 0.1535 | 1.0555 | 0.0809 | 20 | <.0001 |
| | HR | 0.0595 | 0.0213 | 20 | 0.0112 | 1.1166 | 0.043 | 20 | <.0001 | 0.1372 | 0.0294 | 20 | 0.0002 | 0.9902 | 0.0259 | 20 | <.0001 |
| | RR | 0.0368 | 0.0211 | 20 | 0.0959 | 1.1706 | 0.0685 | 20 | <.0001 | 0.071 | 0.0276 | 20 | 0.0181 | 1.0696 | 0.0466 | 20 | <.0001 |

[1] Coefficients for log-linear model $W_t = aW_{ff}^{b}$ where $W_t$ is yield as a proportion of feather- and fat-free empty BW; $W_{ff}$ is feather- and fat-free empty BW; *a* and *b* are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 10. Log-linear regression coefficients[1] for fatpad and gizzard of females and males of six commercial strain crosses[2].

| | | Fat pad | | | | | | | | Gizzard | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sex | Strain | a | SEM | df | P | b | SEM | df | P | a | SEM | df | P | b | SEM | df | P |
| F | PA | 133E-7 | 246E-7 | 20 | 0.5941 | 2.0982 | 0.2308 | 20 | <.0001 | 0.8621 | 0.4048 | 20 | 0.0458 | 0.4507 | 0.0614 | 20 | <.0001 |
| | RA | 0.0001 | 0.0003 | 21 | 0.6769 | 1.7767 | 0.2913 | 21 | <.0001 | 0.8514 | 0.2291 | 21 | 0.0013 | 0.4459 | 0.0345 | 21 | <.0001 |
| | CC | 0.0104 | 0.0199 | 20 | 0.6088 | 1.2263 | 0.2388 | 20 | <.0001 | 1.3737 | 0.576 | 20 | 0.0271 | 0.3921 | 0.0546 | 20 | <.0001 |
| | HH | 0.0011 | 0.0023 | 21 | 0.6292 | 1.5209 | 0.2538 | 21 | <.0001 | 1.0091 | 0.2832 | 21 | 0.0018 | 0.4327 | 0.0366 | 21 | <.0001 |
| | HR | 0.001 | 0.0014 | 21 | 0.4617 | 1.5232 | 0.165 | 21 | <.0001 | 0.8942 | 0.3398 | 21 | 0.0156 | 0.4502 | 0.0489 | 21 | <.0001 |
| | RR | 0.0024 | 0.0023 | 20 | 0.2993 | 1.3838 | 0.1156 | 20 | <.0001 | 0.7979 | 0.349 | 20 | 0.0333 | 0.4762 | 0.056 | 20 | <.0001 |
| M | PA | 0.0106 | 0.029 | 20 | 0.7200 | 1.1579 | 0.3339 | 20 | 0.0024 | 0.9496 | 0.4078 | 20 | 0.0305 | 0.4551 | 0.0539 | 20 | <.0001 |
| | RA | 0.0002 | 0.0003 | 22 | 0.4604 | 1.6143 | 0.1578 | 22 | <.0001 | 1.1237 | 0.411 | 22 | 0.0121 | 0.4267 | 0.0455 | 22 | <.0001 |
| | CC | 0.0002 | 0.0004 | 20 | 0.5985 | 1.627 | 0.2225 | 20 | <.0001 | 1.5177 | 0.7266 | 20 | 0.0497 | 0.3964 | 0.0599 | 20 | <.0001 |
| | HH | 0.0181 | 0.0267 | 20 | 0.5050 | 1.0936 | 0.1766 | 20 | <.0001 | 1.0796 | 0.2739 | 20 | 0.0008 | 0.4293 | 0.0316 | 20 | <.0001 |
| | HR | 0.0006 | 0.0006 | 20 | 0.4001 | 1.5215 | 0.139 | 20 | <.0001 | 0.8438 | 0.3308 | 20 | 0.0191 | 0.4601 | 0.0488 | 20 | <.0001 |
| | RR | 236E-8 | 803E-8 | 20 | 0.7718 | 2.1701 | 0.4031 | 20 | <.0001 | 0.9912 | 0.449 | 20 | 0.0391 | 0.4296 | 0.0562 | 20 | <.0001 |

[1] Coefficients for log-linear model $W_t = aW_{ff}^{b}$ where $W_t$ is yield as a proportion of feather- and fat-free empty BW; $W_{ff}$ is feather- and fat-free empty BW; *a* and *b* are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 11. Log-linear regression coefficients[1] for heart and liver of females and males of six commercial strain crosses[2].

| | | Heart | | | | | | | | Liver | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sex | Strain | a | SEM | df | P | b | SEM | df | P | a | SEM | df | P | b | SEM | df | P |
| F | PA | 0.0698 | 0.0485 | 20 | 0.1653 | 0.6765 | 0.0892 | 20 | <.0001 | 0.2018 | 0.1189 | 16 | 0.1090 | 0.7713 | 0.0778 | 16 | <.0001 |
| | RA | 0.1006 | 0.0602 | 21 | 0.1094 | 0.611 | 0.0757 | 21 | <.0001 | 0.1775 | 0.0847 | 16 | 0.0525 | 0.7868 | 0.062 | 16 | <.0001 |
| | CC | 0.0449 | 0.0304 | 20 | 0.1559 | 0.719 | 0.0858 | 20 | <.0001 | 0.0945 | 0.0404 | 16 | 0.0324 | 0.8676 | 0.0559 | 16 | <.0001 |
| | HH | 0.0216 | 0.0163 | 21 | 0.1980 | 0.8329 | 0.0953 | 21 | <.0001 | 0.0729 | 0.1033 | 17 | 0.4900 | 0.9132 | 0.1865 | 17 | 0.0001 |
| | HR | 0.0273 | 0.0241 | 21 | 0.2700 | 0.7854 | 0.111 | 21 | <.0001 | 0.0878 | 0.0796 | 17 | 0.2854 | 0.8812 | 0.1169 | 17 | <.0001 |
| | RR | 0.0388 | 0.0279 | 20 | 0.1802 | 0.7492 | 0.0904 | 20 | <.0001 | 0.1533 | 0.0795 | 16 | 0.0719 | 0.8056 | 0.0674 | 16 | <.0001 |
| M | PA | 0.0129 | 0.0099 | 20 | 0.2064 | 0.9016 | 0.0936 | 20 | <.0001 | 0.6942 | 0.4047 | 20 | 0.1017 | 0.6016 | 0.0723 | 20 | <.0001 |
| | RA | 0.0483 | 0.0157 | 22 | 0.0056 | 0.7309 | 0.0395 | 22 | <.0001 | 0.2216 | 0.1571 | 22 | 0.1725 | 0.7409 | 0.086 | 22 | <.0001 |
| | CC | 0.0468 | 0.026 | 20 | 0.0865 | 0.7391 | 0.0674 | 20 | <.0001 | 0.5275 | 0.2275 | 20 | 0.0311 | 0.6313 | 0.0528 | 20 | <.0001 |
| | HH | 0.0195 | 0.0223 | 20 | 0.3930 | 0.861 | 0.1383 | 20 | <.0001 | 0.161 | 0.0946 | 20 | 0.1044 | 0.7808 | 0.0712 | 20 | <.0001 |
| | HR | 0.0247 | 0.0209 | 20 | 0.2509 | 0.8284 | 0.1025 | 20 | <.0001 | 0.2566 | 0.1318 | 20 | 0.0656 | 0.7229 | 0.0626 | 20 | <.0001 |
| | RR | 0.0483 | 0.0271 | 20 | 0.0905 | 0.7281 | 0.0682 | 20 | <.0001 | 0.323 | 0.1302 | 20 | 0.0222 | 0.6897 | 0.049 | 20 | <.0001 |

[1] Coefficients for log-linear model $W_t = aW_{ff}^{b}$ where $W_t$ is yield as a proportion of feather- and fat-free empty BW; $W_{ff}$ is feather- and fat-free empty BW; $a$ and $b$ are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 12. Log-linear regression coefficients[1] for empty gut and gut contents of females and males of six commercial strain crosses[2].

| | | Empty gut | | | | | | | | Gut contents | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sex | Strain | a | SEM | df | P | b | SEM | df | P | a | SEM | df | P | b | SEM | df | P |
| F | PA | 1.4877 | 0.723 | 20 | 0.0529 | 0.5641 | 0.0629 | 20 | <.0001 | 0.5846 | 0.809 | 9 | 0.4883 | 0.7498 | 0.1866 | 9 | 0.0030 |
| | RA | 1.6108 | 0.4167 | 21 | 0.0009 | 0.5451 | 0.0329 | 21 | <.0001 | 0.5291 | 0.3123 | 10 | 0.1210 | 0.7389 | 0.0786 | 10 | <.0001 |
| | CC | 2.2002 | 0.6695 | 20 | 0.0037 | 0.5121 | 0.0391 | 20 | <.0001 | 0.5633 | 0.5583 | 9 | 0.3393 | 0.7559 | 0.1325 | 9 | 0.0003 |
| | HH | 1.5158 | 0.4862 | 21 | 0.0052 | 0.5591 | 0.0413 | 21 | <.0001 | 0.0987 | 0.0513 | 11 | 0.0806 | 0.9947 | 0.0691 | 11 | <.0001 |
| | HR | 2.5592 | 0.9083 | 21 | 0.0103 | 0.4888 | 0.0455 | 21 | <.0001 | 0.5371 | 0.4423 | 10 | 0.2526 | 0.7605 | 0.1097 | 10 | <.0001 |
| | RR | 2.2973 | 1.1631 | 20 | 0.0622 | 0.5083 | 0.0646 | 20 | <.0001 | 0.3471 | 0.1296 | 9 | 0.0252 | 0.8112 | 0.0489 | 9 | <.0001 |
| M | PA | 2.1008 | 1.1976 | 20 | 0.0947 | 0.5248 | 0.0711 | 20 | <.0001 | 1.0606 | 0.3989 | 9 | 0.0261 | 0.6332 | 0.0489 | 9 | <.0001 |
| | RA | 0.7596 | 0.5897 | 22 | 0.2111 | 0.661 | 0.0946 | 22 | <.0001 | 0.8574 | 0.4928 | 11 | 0.1098 | 0.6725 | 0.0744 | 11 | <.0001 |
| | CC | 2.3367 | 1.2725 | 20 | 0.0812 | 0.5137 | 0.0672 | 20 | <.0001 | 0.0442 | 0.0852 | 10 | 0.6150 | 1.1143 | 0.2429 | 10 | 0.0010 |
| | HH | 1.9432 | 0.74 | 20 | 0.0162 | 0.5355 | 0.0469 | 20 | <.0001 | 0.0143 | 0.0224 | 10 | 0.5373 | 1.2419 | 0.1971 | 10 | <.0001 |
| | HR | 1.7326 | 0.6169 | 20 | 0.0108 | 0.5466 | 0.0439 | 20 | <.0001 | 1.3051 | 0.7629 | 10 | 0.1179 | 0.6138 | 0.0764 | 10 | <.0001 |
| | RR | 1.4056 | 0.7002 | 20 | 0.0584 | 0.581 | 0.0609 | 20 | <.0001 | 0.154 | 0.2053 | 11 | 0.4691 | 0.9177 | 0.168 | 11 | 0.0002 |

[1] Coefficients for log-linear model $W_t = aW_{ff}^{b}$ where $W_t$ is yield as a proportion of feather- and fat-free empty BW; $W_{ff}$ is feather- and fat-free empty BW; *a* and *b* are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 13. Modified Gompertz regression coefficients[1] for P. major breast muscle of females and males of six commercial strain crosses[2].

| Sex | Strain | $Wt_0$ | SEM | b | SEM | df | P | C | SEM | df | P | d | SEM | df | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | PA | 0.442 | 0.083 | 7.5581 | 0.1253 | 19 | <.0001 | -0.105 | 0.0378 | 19 | 0.0120 | 0.7545 | 0.1047 | 19 | <.0001 |
| | RA | 0.327 | 0.092 | 10.587 | 3.5988 | 20 | 0.0081 | -0.245 | 0.0382 | 20 | <.0001 | 0.374 | 0.1774 | 20 | 0.0479 |
| | CC | 0.368 | 0.049 | 10.173 | 2.0436 | 19 | <.0001 | -0.229 | 0.0314 | 19 | <.0001 | 0.3982 | 0.1201 | 19 | 0.0036 |
| | HH | 0.476 | 0.075 | 9.6902 | 1.7074 | 20 | <.0001 | -0.237 | 0.0269 | 20 | <.0001 | 0.3937 | 0.1046 | 20 | 0.0012 |
| | HR | 0.470 | 0.051 | 8.014 | 0.164 | 20 | <.0001 | -0.126 | 0.0305 | 20 | 0.0005 | 0.6689 | 0.074 | 20 | <.0001 |
| | RR | 0.434 | 0.007 | 9.8096 | 2.1819 | 19 | 0.0002 | -0.225 | 0.0403 | 19 | <.0001 | 0.4077 | 0.1417 | 19 | 0.0097 |
| M | PA | 0.441 | 0.072 | 7.9773 | 0.0884 | 19 | <.0001 | -0.102 | 0.0195 | 19 | <.0001 | 0.7373 | 0.0559 | 19 | <.0001 |
| | RA | 0.383 | 0.065 | 9.0237 | 0.6163 | 21 | <.0001 | -0.166 | 0.0543 | 21 | 0.0060 | 0.5531 | 0.1199 | 21 | 0.0001 |
| | CC | 0.334 | 0.065 | 9.2803 | 0.4967 | 19 | <.0001 | -0.194 | 0.0373 | 19 | <.0001 | 0.5057 | 0.0768 | 19 | <.0001 |
| | HH | 0.552 | 0.014 | 7.8707 | 0.182 | 19 | <.0001 | -0.093 | 0.0442 | 19 | 0.0488 | 0.7684 | 0.1362 | 19 | <.0001 |
| | HR | 0.442 | 0.083 | 8.0874 | 0.1066 | 19 | <.0001 | -0.062 | 0.026 | 19 | 0.0281 | 0.8785 | 0.1147 | 19 | <.0001 |
| | RR | 0.327 | 0.092 | 8.3243 | 0.2123 | 19 | <.0001 | -0.094 | 0.0525 | 19 | 0.0908 | 0.7698 | 0.1595 | 19 | 0.0001 |

[1] Coefficients for modified Gompertz model $W_t = W_0 \exp^{b-b\exp^{-ct^d}}$ where $W_t$ is the weight of the carcass part (g) at time *t* (d); $W_0$ is the carcass part weight (g) at hatch; *b*, *c*, and *d* are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 14. Modified Gompertz regression coefficients[1] for P. minor breast muscle of females and males of six commercial strain crosses[2].

| Sex | Strain | $Wt_0$ | SEM | b | SEM | df | P | c | SEM | df | P | d | SEM | df | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | PA | 0.067 | 0.001 | 8.158 | 0.0946 | 19 | <.0001 | -0.102 | 0.0305 | 19 | 0.0035 | 0.7699 | 0.0855 | 19 | <.0001 |
| | RA | 0.121 | 0.017 | 9.1421 | 1.1885 | 20 | <.0001 | -0.222 | 0.0496 | 20 | 0.0002 | 0.4447 | 0.1196 | 20 | 0.0014 |
| | CC | 0.148 | 0.014 | 8.2984 | 0.3814 | 19 | <.0001 | -0.153 | 0.0322 | 19 | 0.0001 | 0.565 | 0.0771 | 19 | <.0001 |
| | HH | 0.154 | 0.004 | 9.0216 | 1.0442 | 20 | <.0001 | -0.225 | 0.0323 | 20 | <.0001 | 0.4292 | 0.0906 | 20 | 0.0001 |
| | HR | 0.138 | 0.014 | 8.3885 | 0.3719 | 20 | <.0001 | -0.152 | 0.0362 | 20 | 0.0004 | 0.5759 | 0.0837 | 20 | <.0001 |
| | RR | 0.172 | 0.025 | 8.436 | 0.8318 | 19 | <.0001 | -0.173 | 0.0536 | 19 | 0.0044 | 0.5198 | 0.1278 | 19 | 0.0007 |
| M | PA | 0.097 | 0.008 | 8.5133 | 0.197 | 19 | <.0001 | -0.134 | 0.0308 | 19 | 0.0003 | 0.6415 | 0.0719 | 19 | <.0001 |
| | RA | 0.170 | 0.004 | 7.6504 | 0.0883 | 21 | <.0001 | -0.082 | 0.0175 | 21 | 0.0001 | 0.7855 | 0.0614 | 21 | <.0001 |
| | CC | 0.121 | 0.032 | 8.6614 | 0.3827 | 19 | <.0001 | -0.164 | 0.0355 | 19 | 0.0002 | 0.5566 | 0.0786 | 19 | <.0001 |
| | HH | 0.178 | 0.002 | 7.9086 | 0.3179 | 19 | <.0001 | -0.127 | 0.0475 | 19 | 0.0148 | 0.6492 | 0.1182 | 19 | <.0001 |
| | HR | 0.143 | 0.016 | 8.4556 | 0.36 | 19 | <.0001 | -0.121 | 0.0363 | 19 | 0.0034 | 0.6334 | 0.0979 | 19 | <.0001 |
| | RR | 0.161 | 0.010 | 8.1602 | 0.2888 | 19 | <.0001 | -0.124 | 0.0374 | 19 | 0.0037 | 0.6464 | 0.0964 | 19 | <.0001 |

[1] Coefficients for modified Gompertz model $W_t = W_0 \exp^{b-b\exp^{-ct^d}}$ where $W_t$ is the weight of the carcass part (g) at time $t$ (d); $W_0$ is the carcass part weight (g) at hatch; $b$, $c$, and $d$ are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 15. Modified Gompertz regression coefficients[1] for wings of females and males of six commercial strain crosses[2].

| Sex | Strain | df | $Wt_0$ | SEM | b | SEM | P | c | SEM | P | d | SEM | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | PA | 19 | 1.732 | 0.093 | 5.5089 | 0.0607 | <.0001 | -0.115 | 0.018 | <.0001 | 0.7203 | 0.0488 | <.0001 |
| | RA | 20 | 1.819 | 0.425 | 5.3182 | 0.025 | <.0001 | -0.081 | 0.0101 | <.0001 | 0.8397 | 0.0366 | <.0001 |
| | CC | 19 | 2.074 | 0.132 | 5.4991 | 0.1465 | <.0001 | -0.127 | 0.0283 | 0.0003 | 0.6609 | 0.0745 | <.0001 |
| | HH | 20 | 1.934 | 0.020 | 5.4013 | 0.1109 | <.0001 | -0.111 | 0.032 | 0.0024 | 0.7281 | 0.0903 | <.0001 |
| | HR | 20 | 2.056 | 0.029 | 5.3217 | 0.0691 | <.0001 | -0.071 | 0.0171 | 0.0005 | 0.8335 | 0.0708 | <.0001 |
| | RR | 19 | 2.063 | 0.053 | 5.4338 | 0.086 | <.0001 | -0.097 | 0.0212 | 0.0002 | 0.7491 | 0.0672 | <.0001 |
| M | PA | 19 | 1.861 | 0.243 | 5.6033 | 0.0335 | <.0001 | -0.064 | 0.0099 | <.0001 | 0.878 | 0.0444 | <.0001 |
| | RA | 21 | 1.774 | 0.044 | 5.805 | 0.0686 | <.0001 | -0.074 | 0.0163 | 0.0002 | 0.8226 | 0.065 | <.0001 |
| | CC | 19 | 1.768 | 0.072 | 5.6971 | 0.0298 | <.0001 | -0.064 | 0.0086 | <.0001 | 0.8797 | 0.0388 | <.0001 |
| | HH | 19 | 2.397 | 0.006 | 5.6402 | 0.0949 | <.0001 | -0.087 | 0.0162 | <.0001 | 0.7498 | 0.0579 | <.0001 |
| | HR | 19 | 1.727 | 0.061 | 5.7886 | 0.0653 | <.0001 | -0.075 | 0.0146 | <.0001 | 0.812 | 0.0573 | <.0001 |
| | RR | 19 | 1.998 | 0.102 | 5.624 | 0.0503 | <.0001 | -0.058 | 0.0126 | 0.0002 | 0.8931 | 0.0623 | <.0001 |

[1] Coefficients for modified Gompertz model $W_t = W_0 \exp^{b-b\exp^{-ct^d}}$ where $W_t$ is the weight of the carcass part (g) at time *t* (d); $W_0$ is the carcass part weight (g) at hatch; *b*, *c*, and *d* are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 16. Modified Gompertz regression coefficients[1] for back half of females and males of six commercial strain crosses[2].

| Sex | Strain | df | $Wt_0$ | SEM | b | SEM | P | c | SEM | P | d | SEM | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | PA | 19 | 8.364 | 0.107 | 5.1739 | 0.0513 | <.0001 | -0.079 | 0.0125 | <.0001 | 0.8025 | 0.0475 | <.0001 |
| | RA | 20 | 7.939 | 1.487 | 5.3353 | 0.1094 | <.0001 | -0.093 | 0.0247 | 0.0013 | 0.7533 | 0.0824 | <.0001 |
| | CC | 19 | 9.016 | 0.404 | 5.4644 | 0.1999 | <.0001 | -0.118 | 0.0276 | 0.0004 | 0.6532 | 0.0808 | <.0001 |
| | HH | 20 | 8.885 | 1.024 | 5.4086 | 0.1502 | <.0001 | -0.114 | 0.0221 | <.0001 | 0.6666 | 0.066 | <.0001 |
| | HR | 20 | 8.565 | 0.410 | 5.3163 | 0.0632 | <.0001 | -0.084 | 0.0122 | <.0001 | 0.7675 | 0.0445 | <.0001 |
| | RR | 19 | 8.594 | 0.046 | 5.3547 | 0.1154 | <.0001 | -0.078 | 0.0217 | 0.0019 | 0.7843 | 0.0846 | <.0001 |
| M | PA | 19 | 9.222 | 0.850 | 5.4567 | 0.0796 | <.0001 | -0.066 | 0.0164 | 0.0007 | 0.8367 | 0.0726 | <.0001 |
| | RA | 21 | 9.418 | 0.187 | 5.5152 | 0.0798 | <.0001 | -0.056 | 0.0149 | 0.0012 | 0.8757 | 0.0773 | <.0001 |
| | CC | 19 | 8.556 | 0.186 | 5.9286 | 0.1611 | <.0001 | -0.096 | 0.0191 | <.0001 | 0.6957 | 0.0652 | <.0001 |
| | HH | 19 | 11.165 | 0.563 | 5.6675 | 0.1903 | <.0001 | -0.072 | 0.0202 | 0.0021 | 0.7587 | 0.0882 | <.0001 |
| | HR | 19 | 9.201 | 0.084 | 5.4762 | 0.0598 | <.0001 | -0.047 | 0.0109 | 0.0004 | 0.9207 | 0.066 | <.0001 |
| | RR | 19 | 9.657 | 0.059 | 5.5036 | 0.0626 | <.0001 | -0.048 | 0.0107 | 0.0002 | 0.9052 | 0.063 | <.0001 |

[1] Coefficients for modified Gompertz model $W_t = W_0 \exp^{b-b\exp^{-ct^d}}$ where $W_t$ is the weight of the carcass part (g) at time *t* (d); $W_0$ is the carcass part weight (g) at hatch; *b*, *c*, and *d* are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 17. Modified Gompertz regression coefficients[1] for skinless thighs of females and males of six commercial strain crosses[2].

| Sex | Strain | df | $Wt_0$ | SEM | b | SEM | P | c | SEM | P | d | SEM | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | PA | 19 | 2.973 | 0.052 | 5.2065 | 0.0598 | <.0001 | -0.074 | 0.0158 | 0.0002 | 0.8291 | 0.0636 | <.0001 |
| | RA | 20 | 2.384 | 0.207 | 6.0317 | 0.3706 | <.0001 | -0.131 | 0.0429 | 0.0063 | 0.617 | 0.1175 | <.0001 |
| | CC | 19 | 3.129 | 0.044 | 6.0337 | 0.5431 | <.0001 | -0.125 | 0.0398 | 0.0052 | 0.5952 | 0.1248 | 0.0001 |
| | HH | 20 | 2.944 | 0.201 | 5.9266 | 0.3909 | <.0001 | -0.128 | 0.0339 | 0.0012 | 0.6027 | 0.1016 | <.0001 |
| | HR | 20 | 2.488 | 0.317 | 5.7442 | 0.0828 | <.0001 | -0.084 | 0.014 | <.0001 | 0.7583 | 0.051 | <.0001 |
| | RR | 19 | 3.071 | 0.163 | 5.7724 | 0.2888 | <.0001 | -0.097 | 0.0331 | 0.0086 | 0.6894 | 0.1136 | <.0001 |
| M | PA | 19 | 2.978 | 0.436 | 5.7231 | 0.1256 | <.0001 | -0.069 | 0.0239 | 0.0093 | 0.8185 | 0.1017 | <.0001 |
| | RA | 21 | 2.712 | 0.143 | 5.8182 | 0.0721 | <.0001 | -0.046 | 0.0141 | 0.0039 | 0.9372 | 0.0867 | <.0001 |
| | CC | 19 | 3.001 | 0.307 | 6.6829 | 0.6004 | <.0001 | -0.113 | 0.0314 | 0.0019 | 0.5988 | 0.111 | <.0001 |
| | HH | 19 | 3.323 | 0.384 | 6.1685 | 0.3004 | <.0001 | -0.077 | 0.0258 | 0.0078 | 0.7273 | 0.1086 | <.0001 |
| | HR | 19 | 3.534 | 0.313 | 5.5898 | 0.0667 | <.0001 | -0.042 | 0.0103 | 0.0006 | 0.9338 | 0.0684 | <.0001 |
| | RR | 19 | 3.021 | 0.041 | 5.7453 | 0.129 | <.0001 | -0.049 | 0.023 | 0.0451 | 0.905 | 0.1317 | <.0001 |

[1] Coefficients for modified Gompertz model $W_t = W_0 \exp^{b - b\exp^{-ct^d}}$ where $W_t$ is the weight of the carcass part (g) at time $t$ (d); $W_0$ is the carcass part weight (g) at hatch; $b$, $c$, and $d$ are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 18. Modified Gompertz regression coefficients[1] for skinless drums of females and males of six commercial strain crosses[2].

| Sex | Strain | df | $Wt_0$ | SEM | b | SEM | P | c | SEM | P | d | SEM | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | PA | 19 | 2.516 | 0.035 | 5.2006 | 0.066 | <.0001 | -0.096 | 0.0187 | <.0001 | 0.7643 | 0.0599 | <.0001 |
| | RA | 20 | 2.448 | 0.398 | 5.1333 | 0.0611 | <.0001 | -0.07 | 0.0243 | 0.0092 | 0.878 | 0.1013 | <.0001 |
| | CC | 19 | 2.797 | 0.192 | 5.3077 | 0.1434 | <.0001 | -0.116 | 0.0275 | 0.0005 | 0.6827 | 0.0782 | <.0001 |
| | HH | 20 | 2.981 | 0.222 | 5.0348 | 0.096 | <.0001 | -0.111 | 0.0267 | 0.0005 | 0.7232 | 0.0767 | <.0001 |
| | HR | 20 | 2.762 | 0.049 | 5.0956 | 0.0475 | <.0001 | -0.077 | 0.0144 | <.0001 | 0.8288 | 0.0555 | <.0001 |
| | RR | 19 | 2.851 | 0.003 | 5.2443 | 0.1034 | <.0001 | -0.083 | 0.0227 | 0.0016 | 0.7795 | 0.0831 | <.0001 |
| M | PA | 19 | 2.967 | 0.272 | 5.4394 | 0.0728 | <.0001 | -0.071 | 0.0176 | 0.0007 | 0.8333 | 0.0731 | <.0001 |
| | RA | 21 | 2.891 | 0.107 | 5.5002 | 0.0527 | <.0001 | -0.053 | 0.0118 | 0.0002 | 0.9051 | 0.0633 | <.0001 |
| | CC | 19 | 2.825 | 0.217 | 5.6789 | 0.1399 | <.0001 | -0.084 | 0.0264 | 0.0049 | 0.766 | 0.0956 | <.0001 |
| | HH | 19 | 3.510 | 0.136 | 5.6896 | 0.276 | <.0001 | -0.078 | 0.0322 | 0.0252 | 0.7452 | 0.13 | <.0001 |
| | HR | 19 | 3.071 | 0.191 | 5.4544 | 0.0467 | <.0001 | -0.054 | 0.0095 | <.0001 | 0.8885 | 0.0498 | <.0001 |
| | RR | 19 | 3.276 | 0.133 | 5.4155 | 0.0633 | <.0001 | -0.045 | 0.0123 | 0.0017 | 0.9378 | 0.0771 | <.0001 |

[1] Coefficients for modified Gompertz model $W_t = W_0 \exp^{b-b\exp^{-ct^d}}$ where $W_t$ is the weight of the carcass part (g) at time $t$ (d); $W_0$ is the carcass part weight (g) at hatch; $b$, $c$, and $d$ are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 19. Modified Gompertz regression coefficients[1] for gizzard of females and males of six commercial strain crosses[2].

| Sex | Strain | df | $Wt_0$ | SEM | b | SEM | P | c | SEM | P | d | SEM | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | PA | 19 | 1.983 | 0.184 | 2.7628 | 0.066 | <.0001 | -0.071 | 0.0582 | 0.2380 | 0.953 | 0.2581 | 0.0015 |
| | RA | 20 | 1.669 | 0.253 | 3.0434 | 0.0819 | <.0001 | -0.16 | 0.0532 | 0.0069 | 0.6751 | 0.1147 | <.0001 |
| | CC | 19 | 2.552 | 0.089 | 2.5128 | 0.0549 | <.0001 | -0.053 | 0.0501 | 0.3020 | 1.0713 | 0.2988 | 0.0020 |
| | HH | 20 | 2.274 | 0.005 | 2.6679 | 0.0371 | <.0001 | -0.072 | 0.0319 | 0.0360 | 0.9432 | 0.1392 | <.0001 |
| | HR | 20 | 2.306 | 0.213 | 2.805 | 0.1452 | <.0001 | -0.136 | 0.0745 | 0.0825 | 0.6977 | 0.1901 | 0.0015 |
| | RR | 19 | 2.173 | 0.270 | 2.8247 | 0.0506 | <.0001 | -0.026 | 0.0277 | 0.3514 | 1.2429 | 0.3184 | 0.0010 |
| M | PA | 19 | 2.199 | 0.131 | 2.989 | 0.0844 | <.0001 | -0.087 | 0.0547 | 0.1294 | 0.8506 | 0.1996 | 0.0004 |
| | RA | 21 | 2.286 | 0.117 | 3.0014 | 0.1491 | <.0001 | -0.124 | 0.0711 | 0.0959 | 0.7191 | 0.1934 | 0.0013 |
| | CC | 19 | 2.463 | 0.025 | 2.8157 | 0.0565 | <.0001 | -0.031 | 0.0342 | 0.3794 | 1.2024 | 0.3397 | 0.0022 |
| | HH | 19 | 2.548 | 0.034 | 2.902 | 0.1331 | <.0001 | -0.144 | 0.0525 | 0.0128 | 0.6613 | 0.1312 | <.0001 |
| | HR | 19 | 1.779 | 0.054 | 3.7638 | 0.8562 | 0.0003 | -0.216 | 0.0628 | 0.0028 | 0.4619 | 0.1868 | 0.0230 |
| | RR | 19 | 2.110 | 0.201 | 2.8515 | 0.0542 | <.0001 | -0.026 | 0.026 | 0.3237 | 1.2044 | 0.2951 | 0.0006 |

[1] Coefficients for modified Gompertz model $W_t = W_0 \exp^{b-b\exp^{-ct^d}}$ where $W_t$ is the weight of the carcass part (g) at time $t$ (d); $W_0$ is the carcass part weight (g) at hatch; $b$, $c$, and $d$ are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 20. Modified Gompertz regression coefficients[1] for heart of females and males of six commercial strain crosses[2].

| Sex | Strain | df | $Wt_0$ | SEM | b | SEM | P | c | SEM | P | d | SEM | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | PA | 19 | 0.286 | 0.013 | 3.983 | 0.0478 | <.0001 | -0.025 | 0.0232 | 0.2900 | 1.2347 | 0.2692 | 0.0002 |
| | RA | 20 | 0.331 | 0.073 | 3.7655 | 0.0496 | <.0001 | -0.035 | 0.0296 | 0.2518 | 1.1355 | 0.2499 | 0.0002 |
| | CC | 19 | 0.373 | 0.030 | 3.8779 | 0.2536 | <.0001 | -0.104 | 0.0836 | 0.2267 | 0.7439 | 0.2596 | 0.0099 |
| | HH | 20 | 0.309 | 0.017 | 5.4515 | 2.7275 | 0.0594 | -0.186 | 0.0512 | 0.0017 | 0.4382 | 0.2682 | 0.1179 |
| | HR | 20 | 0.378 | 0.083 | 12.77 | 77.709 | 0.8711 | -0.079 | 0.4478 | 0.8613 | 0.325 | 0.3624 | 0.3805 |
| | RR | 19 | 0.348 | 0.024 | 4.047 | 0.218 | <.0001 | -0.087 | 0.0747 | 0.2593 | 0.7992 | 0.268 | 0.0077 |
| M | PA | 19 | 0.350 | 0.038 | 5.129 | 0.8425 | <.0001 | -0.126 | 0.0483 | 0.0174 | 0.5746 | 0.1739 | 0.0037 |
| | RA | 21 | 0.326 | 0.001 | 4.5745 | 0.1731 | <.0001 | -0.106 | 0.0379 | 0.0110 | 0.7124 | 0.1178 | <.0001 |
| | CC | 19 | 0.350 | 0.024 | 4.3498 | 0.127 | <.0001 | -0.07 | 0.0398 | 0.0961 | 0.8544 | 0.1717 | <.0001 |
| | HH | 19 | 0.350 | 0.003 | 4.4561 | 0.1301 | <.0001 | -0.018 | 0.0235 | 0.4477 | 1.1887 | 0.3513 | 0.0031 |
| | HR | 19 | 0.336 | 0.036 | 4.9781 | 0.824 | <.0001 | -0.124 | 0.0843 | 0.1588 | 0.6167 | 0.2615 | 0.0292 |
| | RR | 19 | 0.331 | 0.028 | 4.4508 | 0.1961 | <.0001 | -0.096 | 0.0517 | 0.0804 | 0.7536 | 0.1718 | 0.0003 |

[1] Coefficients for modified Gompertz model $W_t = W_0 \exp^{b-b\exp^{-ct^d}}$ where $W_t$ is the weight of the carcass part (g) at time $t$ (d); $W_0$ is the carcass part weight (g) at hatch; $b$, $c$, and $d$ are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 21. Modified Gompertz regression coefficients[1] for liver of females and males of six commercial strain crosses[2].

| Sex | Strain | df | $Wt_0$ | SEM | b | SEM | P | c | SEM | P | d | SEM | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | PA | 15 | 1.191 | 0.196 | 4.3106 | 0.0961 | <.0001 | -0.061 | 0.0432 | 0.1786 | 0.9828 | 0.2203 | 0.0005 |
| | RA | 15 | 1.054 | 0.082 | 4.7298 | 0.2041 | <.0001 | -0.123 | 0.0553 | 0.0417 | 0.7308 | 0.1566 | 0.0003 |
| | CC | 15 | 1.571 | 0.081 | 4.3178 | 0.2348 | <.0001 | -0.103 | 0.0458 | 0.0404 | 0.7497 | 0.1589 | 0.0003 |
| | HH | 16 | 1.290 | 0.070 | 6.5468 | 8.8456 | 0.4699 | -0.178 | 0.0983 | 0.0893 | 0.4144 | 0.4597 | 0.3808 |
| | HR | 16 | 1.366 | 0.059 | 4.63 | 0.6341 | <.0001 | -0.111 | 0.1038 | 0.2994 | 0.7125 | 0.3421 | 0.0537 |
| | RR | 15 | 1.310 | 0.032 | 4.292 | 0.1229 | <.0001 | -0.054 | 0.0449 | 0.2456 | 0.9948 | 0.2559 | 0.0015 |
| M | PA | 19 | 1.162 | 0.042 | 4.4771 | 0.0442 | <.0001 | -0.038 | 0.0274 | 0.1782 | 1.1244 | 0.21 | <.0001 |
| | RA | 21 | 1.116 | 0.051 | 4.8376 | 0.1948 | <.0001 | -0.082 | 0.0581 | 0.1746 | 0.8101 | 0.2155 | 0.0012 |
| | CC | 19 | 1.368 | 0.092 | 4.3869 | 0.0428 | <.0001 | -0.055 | 0.0227 | 0.0254 | 0.9771 | 0.1209 | <.0001 |
| | HH | 19 | 1.545 | 0.044 | 4.7167 | 0.3516 | <.0001 | -0.113 | 0.0602 | 0.0762 | 0.6765 | 0.1824 | 0.0015 |
| | HR | 19 | 1.103 | 0.021 | 5.5764 | 0.9317 | <.0001 | -0.197 | 0.0567 | 0.0025 | 0.4798 | 0.1559 | 0.0062 |
| | RR | 19 | 1.264 | 0.086 | 4.4958 | 0.0589 | <.0001 | -0.053 | 0.0267 | 0.0625 | 0.9722 | 0.1471 | <.0001 |

[1] Coefficients for modified Gompertz model $W_t = W_0 \exp^{b-b\exp^{-ct^d}}$ where $W_t$ is the weight of the carcass part (g) at time $t$ (d); $W_0$ is the carcass part weight (g) at hatch; $b$, $c$, and $d$ are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 22. Modified Gompertz regression coefficients[1] for empty gut of females and males of six commercial strain crosses[2].

| Sex | Strain | df | $Wt_0$ | SEM | b | SEM | P | c | SEM | P | d | SEM | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | PA | 19 | 4.347 | 0.043 | 3.433 | 0.0634 | <.0001 | -0.072 | 0.0514 | 0.1779 | 0.9425 | 0.2199 | 0.0004 |
| | RA | 20 | 3.383 | 0.258 | 3.7851 | 0.0699 | <.0001 | -0.153 | 0.0449 | 0.0028 | 0.6947 | 0.097 | <.0001 |
| | CC | 19 | 4.922 | 0.247 | 3.3123 | 0.035 | <.0001 | -0.056 | 0.0284 | 0.0616 | 1.0275 | 0.1544 | <.0001 |
| | HH | 20 | 4.578 | 0.051 | 3.4047 | 0.0562 | <.0001 | -0.082 | 0.0439 | 0.0774 | 0.8947 | 0.1657 | <.0001 |
| | HR | 20 | 4.304 | 0.143 | 3.4157 | 0.0334 | <.0001 | -0.057 | 0.0297 | 0.0670 | 1.0313 | 0.1585 | <.0001 |
| | RR | 19 | 4.059 | 0.190 | 3.5436 | 0.0428 | <.0001 | -0.032 | 0.0256 | 0.2309 | 1.192 | 0.2424 | <.0001 |
| M | PA | 19 | 4.225 | 0.011 | 3.6711 | 0.066 | <.0001 | -0.055 | 0.045 | 0.2385 | 1.0088 | 0.2472 | 0.0006 |
| | RA | 21 | 4.678 | 0.172 | 4.3839 | 0.9026 | <.0001 | -0.136 | 0.0897 | 0.1432 | 0.5875 | 0.2766 | 0.0457 |
| | CC | 19 | 4.712 | 0.026 | 3.6033 | 0.059 | <.0001 | -0.039 | 0.0348 | 0.2799 | 1.1063 | 0.2673 | 0.0006 |
| | HH | 19 | 5.071 | 0.071 | 3.5748 | 0.0507 | <.0001 | -0.059 | 0.0279 | 0.0492 | 0.9567 | 0.1432 | <.0001 |
| | HR | 19 | 3.695 | 0.313 | 3.8796 | 0.0817 | <.0001 | -0.092 | 0.0475 | 0.0690 | 0.8327 | 0.1604 | <.0001 |
| | RR | 19 | 4.161 | 0.393 | 3.804 | 0.0415 | <.0001 | -0.019 | 0.0146 | 0.2142 | 1.2786 | 0.2236 | <.0001 |

[1] Coefficients for modified Gompertz model $W_t = W_0 \exp^{b - b\exp^{-ct^d}}$ where $W_t$ is the weight of the carcass part (g) at time *t* (d); $W_0$ is the carcass part weight (g) at hatch; *b*, *c*, and *d* are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 23. Modified Gompertz regression coefficients[1] for abdominal fatpad of females and males of six commercial strain crosses[2].

| Sex | Strain | df | $Wt_0$ | SEM | P | b | SEM | P | c | SEM | P | d | SEM | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | PA | 18 | 1.3406 | 7.8795 | 0.8668 | 6.0046 | 6.6288 | 0.3770 | -0.024 | 0.1158 | 0.8371 | 0.9837 | 1.0633 | 0.3671 |
| | RA | 19 | 7.273 | 15.191 | 0.6376 | 3.8575 | 2.2854 | 0.1078 | -91E-5 | 0.005 | 0.8574 | 1.7481 | 1.2509 | 0.1784 |
| | CC | 18 | 6.5664 | 12.291 | 0.5997 | 3.6328 | 1.9115 | 0.0735 | -45E-5 | 0.0021 | 0.8362 | 2.0094 | 1.0983 | 0.0839 |
| | HH | 19 | 1.2942 | 13.556 | 0.9249 | 6.0076 | 12.016 | 0.6228 | -0.048 | 0.3505 | 0.8914 | 0.8228 | 1.6109 | 0.6154 |
| | HR | 19 | 1.7861 | 7.8123 | 0.8216 | 5.1557 | 4.5189 | 0.2681 | -0.01 | 0.04 | 0.8100 | 1.2724 | 0.9059 | 0.1763 |
| | RR | 18 | 0.1962 | 3.1658 | 0.9513 | 7.3454 | 16.877 | 0.6686 | -0.05 | 0.3592 | 0.8910 | 0.8761 | 1.531 | 0.5742 |
| M | PA | 18 | 1.0433 | 11.436 | 0.9283 | 5.1498 | 11.124 | 0.6490 | -0.013 | 0.1109 | 0.9103 | 1.2728 | 1.9625 | 0.5248 |
| | RA | 20 | 0.0445 | 1.3687 | 0.9744 | 8.4275 | 31.311 | 0.7906 | -0.086 | 0.7624 | 0.9109 | 0.804 | 1.8454 | 0.6678 |
| | CC | 18 | 0.0725 | 3.0465 | 0.9813 | 10.447 | 57.977 | 0.8590 | -0.168 | 1.9358 | 0.9316 | 0.4635 | 2.6274 | 0.8619 |
| | HH | 18 | 5.482 | 10.977 | 0.6235 | 3.5363 | 2.0324 | 0.0989 | -76E-5 | 0.0036 | 0.8346 | 1.9325 | 1.1119 | 0.0993 |
| | HR | 18 | 4.3884 | 6.8028 | 0.5270 | 4.0236 | 1.6355 | 0.0242 | -0.002 | 0.0052 | 0.7542 | 1.6471 | 0.7137 | 0.0331 |
| | RR | 18 | 0.5679 | 9.9815 | 0.9553 | 7.4308 | 24.624 | 0.7663 | -0.054 | 0.5964 | 0.9291 | 0.7256 | 2.5766 | 0.7814 |

[1] Coefficients for modified Gompertz model $W_t = W_0 \exp^{b-b\exp^{-ct^d}}$ where $W_t$ is the weight of the carcass part (g) at time $t$ (d); $W_0$ is the carcass part weight (g) at hatch; $b$, $c$, and $d$ are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 24. Modified Gompertz regression coefficients[1] for gut contents of females and males of six commercial strain crosses[2].

| Sex | Strain | df | $Wt_0$ | SEM | P | b | SEM | P | c | SEM | P | d | SEM | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| F | PA | 7 | 10.123 | 21.031 | 0.6449 | 2.9598 | 2.0865 | 0.1990 | -38E-5 | 0.0024 | 0.8813 | 2.4613 | 1.7902 | 0.2116 |
| | RA | 8 | 3.3164 | 8.9417 | 0.7203 | 4.0189 | 2.7487 | 0.1818 | -0.032 | 0.0834 | 0.7133 | 1.1829 | 0.6808 | 0.1205 |
| | CC | 7 | 5.7754 | 17.261 | 0.7477 | 3.592 | 3.0082 | 0.2713 | -0.008 | 0.0344 | 0.8234 | 1.5819 | 1.1461 | 0.2100 |
| | HH | 9 | 1.3364 | 10.507 | 0.9016 | 5.7419 | 9.0184 | 0.5402 | -0.152 | 0.5857 | 0.8004 | 0.6422 | 0.9711 | 0.5250 |
| | HR | 8 | 0.7267 | 11.966 | 0.9531 | 5.754 | 16.751 | 0.7401 | -0.088 | 0.6503 | 0.8959 | 0.9202 | 1.811 | 0.6251 |
| | RR | 7 | 1.5864 | 8.1333 | 0.8509 | 4.9658 | 5.2611 | 0.3767 | -0.053 | 0.1834 | 0.7802 | 1.0336 | 0.8747 | 0.2759 |
| M | PA | 7 | 0.0985 | 4.4144 | 0.9828 | 7.7454 | 45.895 | 0.8708 | -0.23 | 2.4357 | 0.9273 | 0.6399 | 2.4089 | 0.7982 |
| | RA | 9 | 0.0648 | 5.5228 | 0.9909 | 8.1771 | 87.298 | 0.9274 | -0.255 | 4.692 | 0.9579 | 0.6164 | 4.1975 | 0.8865 |
| | CC | 8 | 0.0129 | 8.36 | 0.9988 | 9.8648 | 662.4 | 0.9885 | -0.348 | 34.504 | 0.9922 | 0.5395 | 21.76 | 0.9808 |
| | HH | 8 | 0.0051 | 3.0736 | 0.9987 | 10.833 | 618.64 | 0.9865 | -0.401 | 31.335 | 0.9901 | 0.5061 | 16.851 | 0.9768 |
| | HR | 8 | 0.004 | 0.6728 | 0.9954 | 11.074 | 171.38 | 0.9501 | -0.413 | 8.6014 | 0.9629 | 0.4996 | 4.4684 | 0.9137 |
| | RR | 9 | 0.0016 | 0.7151 | 0.9982 | 11.999 | 445.19 | 0.9791 | -0.46 | 21.315 | 0.9832 | 0.4747 | 9.6481 | 0.9618 |

[1] Coefficients for modified Gompertz model $W_t = W_0 \exp^{b-b\exp^{-ct^d}}$ where $W_t$ is the weight of the carcass part (g) at time $t$ (d); $W_0$ is the carcass part weight (g) at hatch; $b$, $c$, and $d$ are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 25. Log-linear regression coefficients[1] for chemical components of females and males of six commercial strain crosses[2].

| | | Female | | | | | | Male | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Part | Strain | a | SEM | P | b | SEM | P | a | SEM | P | b | SEM | P |
| Ash | PA | 0.0361 | 0.0195 | 0.0711 | 0.9857 | 0.0682 | <.0001 | 0.0444 | 0.0119 | 0.0006 | 0.9629 | 0.0324 | <.0001 |
| | RA | 0.1316 | 0.0768 | 0.0944 | 0.7983 | 0.0731 | <.0001 | 0.0560 | 0.0194 | 0.0063 | 0.9219 | 0.0412 | <.0001 |
| | CC | 0.0526 | 0.0238 | 0.0324 | 0.9273 | 0.0562 | <.0001 | 0.0532 | 0.0162 | 0.0021 | 0.9345 | 0.0365 | <.0001 |
| | HH | 0.0345 | 0.0132 | 0.0117 | 0.9780 | 0.0478 | <.0001 | 0.0619 | 0.0229 | 0.0104 | 0.9101 | 0.0443 | <.0001 |
| | HR | 0.0816 | 0.0448 | 0.0762 | 0.8579 | 0.0686 | <.0001 | 0.0584 | 0.0176 | 0.0019 | 0.9137 | 0.0361 | <.0001 |
| | RR | 0.0700 | 0.0254 | 0.0085 | 0.8903 | 0.0449 | <.0001 | 0.0333 | 0.0164 | 0.0497 | 0.9891 | 0.0588 | <.0001 |
| Protein | PA | 0.2489 | 0.0770 | 0.0023 | 0.9727 | 0.0391 | <.0001 | 0.2009 | 0.0620 | 0.0025 | 1.0017 | 0.0374 | <.0001 |
| | RA | 0.3138 | 0.1349 | 0.0252 | 0.9433 | 0.0535 | <.0001 | 0.1605 | 0.0435 | 0.0007 | 1.0212 | 0.0322 | <.0001 |
| | CC | 0.3624 | 0.1006 | 0.0008 | 0.9246 | 0.0345 | <.0001 | 0.2498 | 0.0671 | 0.0006 | 0.9753 | 0.0322 | <.0001 |
| | HH | 0.2626 | 0.0574 | <.0001 | 0.9635 | 0.0274 | <.0001 | 0.2928 | 0.1066 | 0.0093 | 0.9549 | 0.0435 | <.0001 |
| | HR | 0.2439 | 0.0676 | 0.0009 | 0.9774 | 0.0345 | <.0001 | 0.2333 | 0.0580 | 0.0002 | 0.9816 | 0.0298 | <.0001 |
| | RR | 0.3049 | 0.0707 | <.0001 | 0.9444 | 0.0287 | <.0001 | 0.2194 | 0.0689 | 0.0029 | 0.9881 | 0.0374 | <.0001 |
| Water | PA | 0.7723 | 0.0589 | <.0001 | 0.9977 | 0.0096 | <.0001 | 0.7916 | 0.0727 | <.0001 | 0.9945 | 0.0111 | <.0001 |
| | RA | 0.6888 | 0.0802 | <.0001 | 1.0130 | 0.0145 | <.0001 | 0.7871 | 0.0614 | <.0001 | 0.9973 | 0.0093 | <.0001 |
| | CC | 0.6775 | 0.0429 | <.0001 | 1.0154 | 0.0078 | <.0001 | 0.7756 | 0.0523 | <.0001 | 0.9972 | 0.0081 | <.0001 |
| | HH | 0.7514 | 0.0385 | <.0001 | 1.0021 | 0.0064 | <.0001 | 0.7185 | 0.0632 | <.0001 | 1.0071 | 0.0105 | <.0001 |
| | HR | 0.7215 | 0.0580 | <.0001 | 1.0063 | 0.0100 | <.0001 | 0.7700 | 0.0477 | <.0001 | 0.9986 | 0.0074 | <.0001 |
| | RR | 0.7161 | 0.0397 | <.0001 | 1.0078 | 0.0068 | <.0001 | 0.7843 | 0.0659 | <.0001 | 0.9967 | 0.0100 | <.0001 |
| Lipid | PA | 0.0030 | 0.0024 | 0.2096 | 1.6080 | 0.0978 | <.0001 | 0.0861 | 0.0808 | 0.2933 | 1.1178 | 0.1133 | <.0001 |
| | RA | 0.0096 | 0.0068 | 0.1671 | 1.4384 | 0.0873 | <.0001 | 0.0436 | 0.0191 | 0.0285 | 1.1856 | 0.0519 | <.0001 |
| | CC | 0.1251 | 0.0967 | 0.2027 | 1.1168 | 0.0955 | <.0001 | 0.0430 | 0.0274 | 0.1239 | 1.1969 | 0.0757 | <.0001 |
| | HH | 0.0161 | 0.0142 | 0.2618 | 1.3859 | 0.1091 | <.0001 | 0.0581 | 0.0472 | 0.2264 | 1.1736 | 0.0966 | <.0001 |
| | HR | 0.0204 | 0.0147 | 0.1731 | 1.3479 | 0.0889 | <.0001 | 0.0293 | 0.0191 | 0.1327 | 1.2518 | 0.0775 | <.0001 |
| | RR | 0.0149 | 0.0110 | 0.1820 | 1.3793 | 0.0900 | <.0001 | 0.0054 | 0.0075 | 0.4737 | 1.4549 | 0.1633 | <.0001 |

[1] Coefficients for log-linear model $W_t = aW_{ff}^{b}$ where $W_t$ is weight of each component as a proportion of feather- and fat-free empty BW; $W_{ff}$ is feather- and fat-free empty BW; *a* and *b* are least squares estimated coefficients.

[2] Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

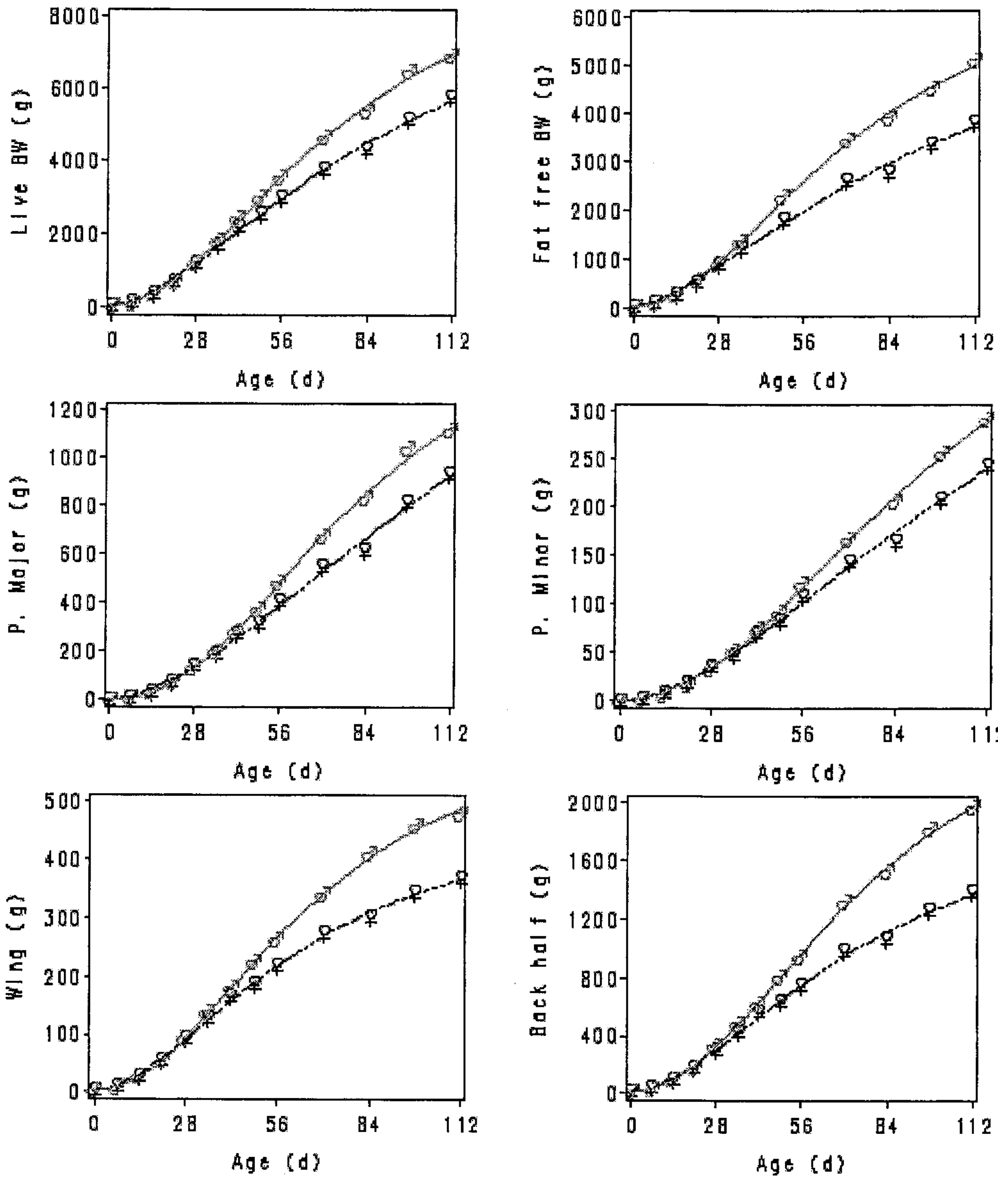


Figure 1. Plots of broiler live weight, fat and feather free empty carcass weight, and the weight of commercially important broiler parts from hatch to 112 d. Average data from males (♂; solid lines) and females (♀; dotted lines) of six commercial strain crosses.

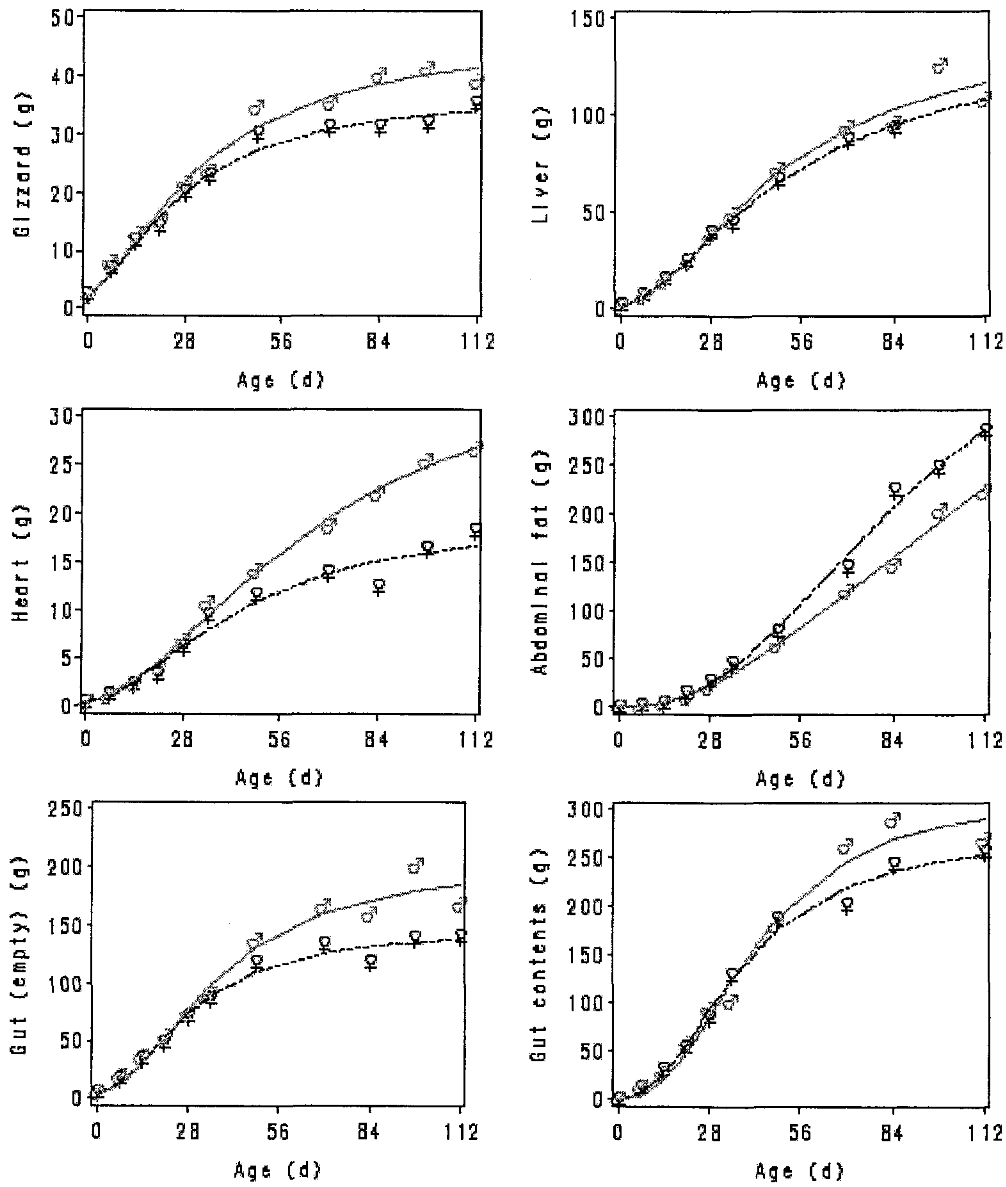


Figure 2. Plots of broiler gizzard, liver, heart, abdominal fat, gut, and gut contents weights from hatch to 112 d. Average data from males (♂; solid lines) and females (♀; dotted lines) of six commercial strain crosses. Due to a puberty related growth phase of the liver of females after 84 d, data after 84 d is not included for females.

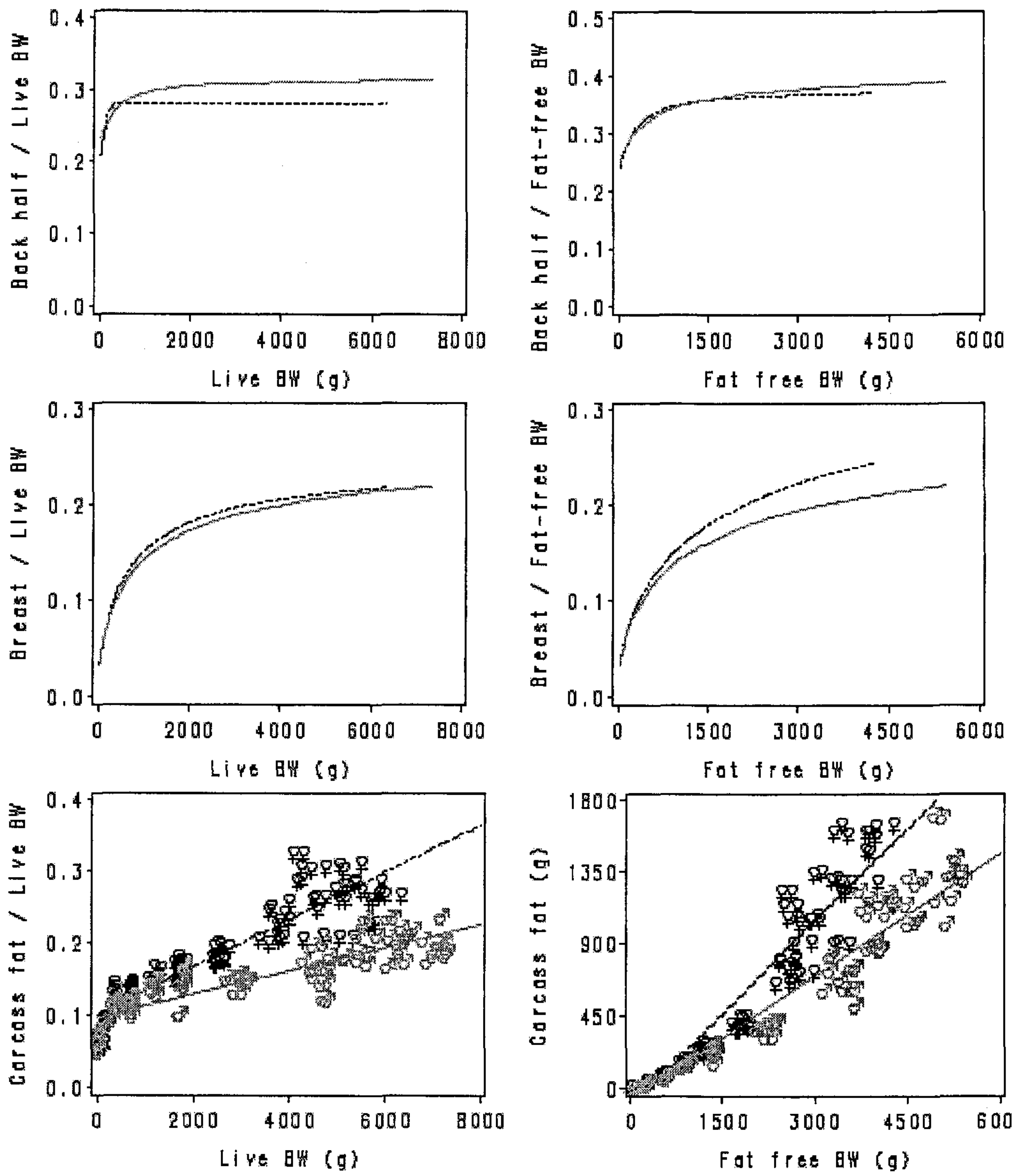


Figure 3. Plots of back half, breast meat yield, and carcass fat as a proportion of live BW (left-hand column), and fat-free empty BW (right-hand column). Data are from males (♂; solid lines) and females (♀; dotted lines) of six commercial strain crosses.

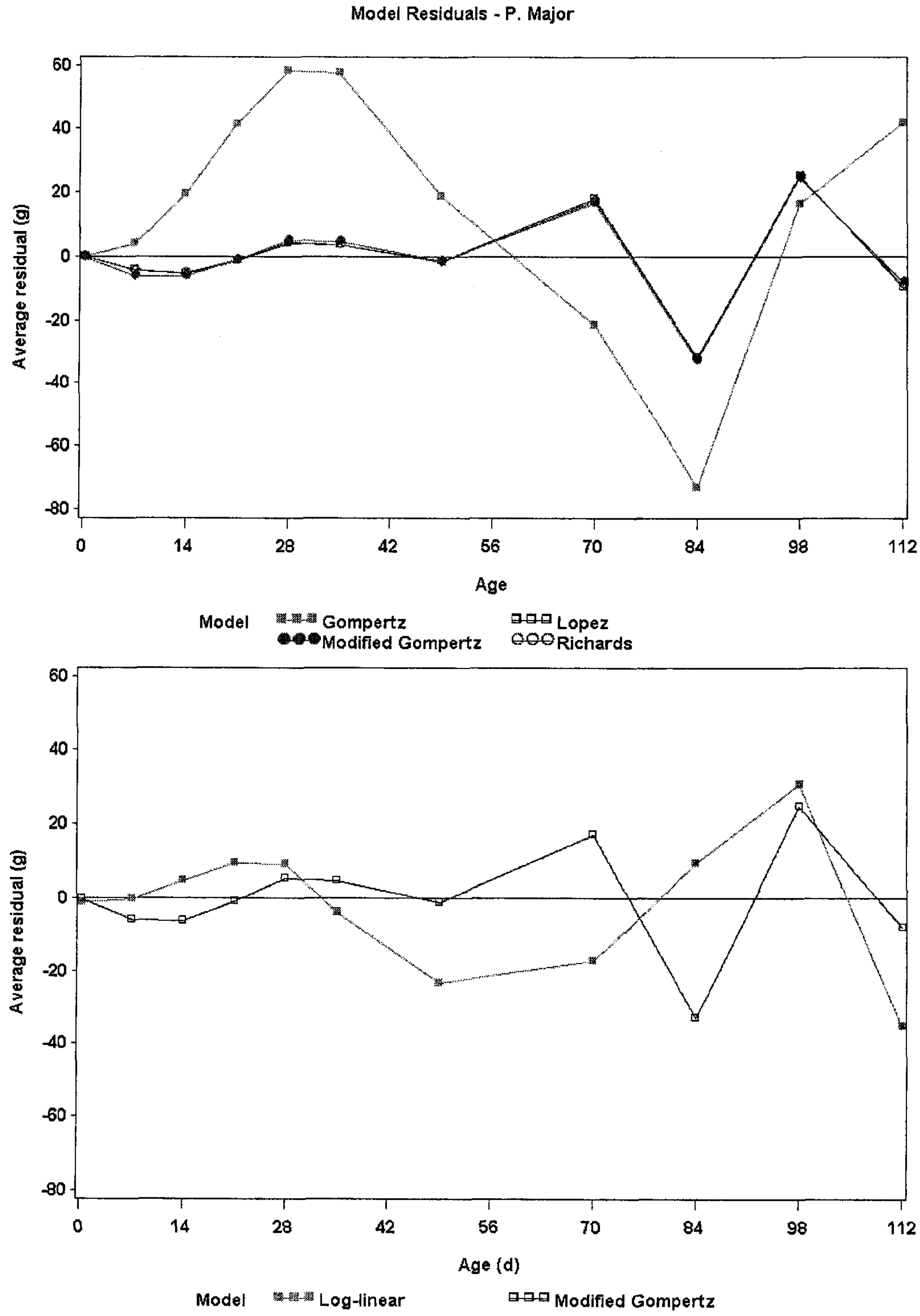


Figure 4. Plot of average residuals from four Sigmoidal prediction models (upper graph) and from Modified Gompertz (Sigmoidal) and log-linear (Diminishing Returns) models (lower graph) for P. major weight of males and females of six commercial broiler strain crosses.

***References***

AFLB. 2000. Standard Operation Procedures for Agri-Food Laboratories Branch (AFLB), Food Safety Division, Alberta Agriculture, Food and Rural Development, Edmonton, Alberta, Canada.

Cant, J. P., B. W. McBride, and W. J. Croom Jr. 1996. The regulation of intestinal metabolism and its impact on whole animal energetics. J. Anim. Sci. 74:2541-2553.

Darmani Kuhi, H., E. Kebreab, S. Lopez, and J. France. 2003. An evaluation of different growth functions for describing the profile of live weight with time (age) in meat and egg strains of chicken. Poultry Sci. 82:1536-1543.

Emmans, G. C. 1981. A model of the growth and feed intake of *ad libitum* fed animals, particularly poultry. In Computers in Animal Production - Occasional Publication No. 5. The British Society of Animal Production, Hillyer, G. M. C. T. Whittemore R. G. Gunn, eds. Harrogate.

Goliomytis, M., E. Panopoulou, and E. Rogdakis. 2003. Growth curves for body weight and major component parts, feed consumption, and mortality of male broiler chickens raised to maturity. Poultry Sci. 82:1061-1068.

Gous, R. M., E. T. Moran Jr., H. R. Stilborn, G. D. Bradford, and G. C. Emmans. 1999. Evaluation of the parameters needed to describe the overall growth, the chemical growth, and the growth of feathers and breast muscles of broilers. Poultry Sci. 78:812-821.

Hancock, C. E., G. D. Bradford, G. C. Emmans, and R. M. Gous. 1995. The evaluation of the growth parameters of six strains of commercial broiler chickens. Br. Poultry Sci. 36:247-264.

Havenstein, G. B., P. R. Ferket, and M. A. Qureshi. 2003. Carcass composition and yield of 1957 versus 2001 broilers when fed representative 1957 and 2001 broiler diets. Poultry Sci. 82:1509-1518.

Kalinowski, A., E. T. Moran Jr, and C. L. Wyatt. 2003. Methionine and cystine requirements of slow- and fast-feathering broiler males from three to six weeks of age. Poultry Sci. 82:1428-1437.

Lopez, S., J. France, W. J. Gerrits, M. S. Dhanoa, D. J. Humphries, and J. Dijkstra. 2000. A generalized Michaelis-Menten equation for the analysis of growth. J. Anim. Sci. 78:1816-1828.

McNurlan, M. A. and P. J. Garlick. 1980. Contribution of rat liver and gastrointestinal tract to whole-body protein synthesis in the rat. Biochem J. 186:381-383.

Mendes, A. A., S. E. Watkins, J. A. England, E. A. Saleh, A. L. Waldroup, and P. W. Waldroup. 1997. Influence of dietary lysine levels and arginine:lysine ratios on performance of broilers exposed to heat or cold stress during the period of three to six weeks of age. Poultry Sci. 76:472-481.

Mills, B. L., F. R. van de Voort, and W. R. Usborne. 1983. Mojonnier method as reference for infrared determination of fat in meat products. J. Assoc. Off. Anal. Chem. 66:1048-1050.

NRC. 1994. Nutrient Requirements of Poultry. National Research Council. National Academy Press, Washington D.C.

Orr, H. L., Hunt, C., and Randall, C. J. 1984. Yield of carcass, parts, meat, skin, and bone of eight strains of broilers. Poultry Sci. 63:2197-2200.

Osbaldiston, G. W. 1967. Carcass measurement in broiler chickens. The Poultry Rev. 6:63-69.

Peak, S. D., T. J. Walsh, C. E. Benton, J. Brake, and P. L. M. van Horne. 2000. Effects of two planes of nutrition on performance and uniformity of four strains of broiler chicks. J. Appl. Poultry Res. 9:185-194.

Peek, M. S., E. Russek-Cohen, D. A. Wait, and I. N. Forseth. 2002. Physiological response curve analysis using nonlinear mixed models. Oecologia 132:175-180.

SAS System, Version 8.02. Copyright © 1999-2001 by SAS Institute, Inc., Cary, NC, USA.

Scheuermann, G. N., S. F. Bilgili, J. B. Hess, and D. R. Mulvaney. 2003. Breast muscle development in commercial broiler chickens. Poultry Sci. 82:1648-1658.

Smith, E. R. and G. M. Pesti. 1998. Influence of broiler strain cross and dietary protein on the performance of broilers. Poultry Sci. 77:276-281.

Smith, E. R., G. M. Pesti, R. I. Bakalli, G. O. Ware, and J. F. Menten. 1998. Further studies on the influence of genotype and dietary protein on the performance of broilers. Poultry Sci. 77:1678-1687.

Talpaz, H., Cohen, M., and Fancher, B. I. 2000. Ranking broiler strain cross performance in commercial complexes under varying nutrient concentrations. Proceedings of the Annual Nutrition Conference, Fayetteville, Arkansas. The Poultry Federation.

Vieira, S. L. and E. T. Moran Jr. 1998. Broiler yields using chicks from extremes in breeder age and dietary propionate. J. Appl. Poultry Res. 7:320-327.

# CHAPTER 6. A BIOECONOMIC BROILER PROCESSING MODEL

**Abstract**. In this study a general broiler processing model is developed which includes important biological and economic parameters. The model incorporates processing infrastructure and process-related costs, with commercial strain-specific biological yield data. The model is highly customizable, offering flexibility in the types of processes, products, and packaging required for a processing operation. An optimization algorithm allows the user to identify the optimum strain and market body weight for any specified product mix. Six commercial broiler strain-crosses were evaluated under two market scenarios. In a whole bird market scenario, a modest strain advantage was apparent. Male broilers were more profitable in the whole bird scenario. In a value-added market scenario where a premium is elicited for white meat, a clear strain advantage emerged, and females were more profitable at lower market BW. The model provides a framework for consistently predicting economic outcomes of alternative market scenarios and providing insights that will help poultry supply chain decision makers to identify strains and products most suited to their individual needs.

Abbreviation key: BCSCM = Broiler Chicken Supply Chain Model; V-A = value-added

### *Background*

Broiler processing is a complex system, requiring large capital inputs and numerous interconnected processes. Optimal economic performance is a function of the costs and revenues of the processing system. The strain decision can influence optimal economic performance by way of differences in production efficiencies and meat yields of commercially available broiler strains. The types of products can also affect profitability because of differential yield of white, dark, total meat fractions by genetic (strain) and sexual polymorphism, and through investment in specialized equipment. Because of the complexity of the system and the magnitude of genetic variation available commercially, finding an optimum strain for a specific product mix is a complex challenge. For this purpose, a Broiler Chicken Supply Chain Model (BCSCM[1]) was developed. The model incorporates production costs at the hatching egg and broiler level into a processing model, providing an integrated analysis framework with which a supply chain can evaluate the economic potential of candidate commercial broiler strains for their system. The hatching egg and broiler modules of BCSCM have been described elsewhere (Zuidhof, 2004a; Zuidhof, 2004b).

### *Objective*

For the current analysis, a bioeconomic processing simulation model has been developed to objectively compare males and females of a variety of commercial broiler strain crosses. The primary objective of the model is to support the strain

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[1] Broiler Chicken Supply Chain Model, Version 2.46, copyright © 2004 by Alberta Agriculture, Food and Rural Development.

selection decision for any commercial processing plant by predicting their economic potential for any product mix. Further, strain-specific insights into the effect of market BW on profitability are needed to optimize harvesting age. With this type of tool decision makers can objectively evaluate candidate strain crosses prior to making potentially costly changes to genetic programs, as well as the implications of sex and market BW for their operations.

***Model overview***

Product demand is specified by orders that the processing plant is required to fill. A flock of a specific sex, strain cross or combination thereof, along with a target market BW, is simulated to fill the order. Strain- and sex- specific growth and yield parameters are used to calculate carcass weight, yield and carcass part yields for each individual. Processing of carcasses is then simulated. In the simulation all carcasses are subjected to a primary processing protocol, yielding the most basic product, an eviscerated whole carcass. Costs associated with further processing and packaging are then assigned to fill the orders. To fill the maximum number of orders, products with the most constraints (size or weight) are processed first. In the simulation, all carcass parts of all birds are accounted separately, yielding diagnostic data needed to understand where excess product inefficiencies may reside. The simulation can be scaled to any plant capacity.

***Processing infrastructure***

Simulation of the processing infrastructure is general and customizable for flexibility. Entry of total daily plant throughput (kg/day) is required in order to scale the simulation to the daily production volume of the processing plant. The number of days of operation per week is needed to calculate annual production volume, important for scaling infrastructure costs and assigning appropriate fixed costs to products. Infrastructure can be added under five headings: land and buildings; primary processing equipment; secondary processing equipment; administrative equipment; and mobile equipment. Detailed entries or total capital cost estimates can be entered for each category. Separate depreciation rates can be applied to buildings, equipment, and mobile equipment. A description of each piece of equipment or building purchased, the purchase cost, date acquired, and a designation to a specific process or to general operations must be supplied for every capital item or group of items, depending on the level of detail desired by the user. The purchase date allows for nonlinear depreciation rates to be applied to every piece of equipment or building individually. The specification of a process for each capital item allows the model to assign fixed costs in a process-specific manner.

Loan information, including the date acquired, the process to which the cost of the loan should be applied, the principal, term, and interest rate allow the model to designate financing costs to specific processes. A simulation date is specified when the simulation is run to determine time-relevant interest and depreciation costs. Direct input of insurance and tax costs complete the fixed cost inputs. Fixed costs, which include the sum of interest, insurance, tax, and depreciation costs, are reported as an annual total, and on a per-kg basis, based on the annual production volume.

### *Processing operations*

***Process identification.*** Post-evisceration processes such as specific cutting processes, seasoning or cooking, and the costs associated with those processes can be identified and associated with any product. Packaging, a special type of process, is handled in a similar manner, allowing for complete customization of the simulation to a specific processing plant and product repertoire.

***Product definition.*** Simulation of carcass processing depends heavily on the definition of products. Products are assigned a name, and the carcass parts included in the product are identified. To account for process-specific costs, the processes required to manufacture the product must be specified. Alternatively, general costs can be estimated and specified elsewhere in the simulation. If the carcass parts included in the product are cut into smaller pieces, the number of pieces can be specified, allowing the model to identify the size of the pieces. This definition also allows the model to account for parts and weights required to satisfy product demand, and to estimate the approximate number of birds required to produce the products. A process-specific production cost is calculated uniquely for each product.

***Product demand.*** After products and processes have been defined, product demand may be managed by way of a virtual order sheet. The amount of each product (pieces or weight) to be produced, along with any minimum or maximum size specifications and packaging details are specified. A wholesale price for each product is also specified within each order, enabling the model to calculate the contribution of product- and order- specific revenues to overall revenue.

### *Processing simulation*

***Yield of carcass parts.*** Broilers are simulated using a growth simulation described previously (Zuidhof, 2004b). This simulation estimates strain- and sex-specific broiler production costs, an important factor in the strain decision and other management decisions. Feather weight and feather- and fat-free empty body weight (FFFEBM) are also estimated. For each simulated individual the following carcass part weights are estimated as a function of FFFEBM, using a log-linear proportional yield model (Zuidhof, 2004c): P. Major; P. Minor, back half; skinless drums and thighs; wings; liver; heart; gizzard; abdominal fatpad; total gastrointestinal tract; and total viscera. Using the log-linear diminishing returns methodology and data from Zuidhof (2004c) eviscerated carcass without giblets (WOG) yield parameters were estimated as a function of FFFEBM. The coefficients for predicting carcass WOG yield are reported in Table 1. Other parts not reported previously were included, some stochastically, in the simulation. The formulae used to estimate other carcass part weights are reported in Table 2.

***Processing simulation.*** After generating a distribution of broiler and broiler part weights, costs and revenues associated with all orders are simulated. The number of carcasses required is calculated from the mean carcass and carcass part yields of the genotypes selected, and the total product demand. If the user chooses to scale the order to the daily plant capacity, the order is adjusted such that ratio of products matches the total daily capacity of the processing plant. The number of birds simulated is then also scaled to the total specified production. A scaling factor is calculated as $Scale = W_{req} / W_{sim}$ where *Scale* is the scaling factor, $W_{req}$ is the weight of product required in the simulation, and $W_{sim}$ is the total eviscerated weight of chicken in the simulation. This scaling factor determines how many times the part weights from a simulated individual can be assigned to fill demand. For example, if plant capacity is 80,000 kg per day, the set of orders might require 52,000 birds. If the default 500 birds are simulated in such a scenario, the carcass and carcass part weights from each simulated bird would be used 104 times.

Primary processing costs are assigned to each carcass (scaled to plant volume). Secondary process-specific and packaging costs are then assigned, based on the processes and packaging required for each product in each order. User-specified general variable costs beyond those included in the process-specific costs, including labour, maintenance, water, electricity, fuel, and natural gas, are also calculated. These general variable costs are input as daily costs, and divided over the total daily product output. Fixed costs, calculated on an annual basis, are divided over the total volume of production extrapolated from the daily production volume.

***Order processing.*** Before orders are processed, the weight of the relevant parts of all birds simulated for processing are evaluated for suitability for the products ordered. Where there are product size constraints (minimum or maximum weight), suitability is determined where the sum of the weights of the carcass parts included in the product fall within the weight constraints. For each order, the number of suitable and unsuitable birds is determined. The order with the least suitable birds is processed first to maximize the number of orders that can be filled.

Birds are processed to fill orders, the most highly constrained of which are filled first. While an order remains unfilled, the suitability of each consecutive bird determines whether or not it can be used to fill the order. If the bird meets the weight requirements, and has not been completely "used" previously, the parts required in the current order are flagged as used, and the order is incrementally filled with a scaled amount of product (weight or pieces) from the simulated bird. If the amount of product is equal to or greater than the amount of product available from the current bird (scaled), then the parts of the bird required for the product are marked used, and are unavailable for other products. If less than the full amount is required, the proportion required is marked as used, and the remaining portion remains available for use in other orders. This process continues until all orders have been filled, or until no birds remain that meet the specifications in the order.

***Simulation output.*** Economic results of the simulation are presented as gross costs, revenues, and margins, as well as on a per-kg live and per-kg meat basis. Margin is calculated as the difference between income and all costs. The contribution of each product to the total cost and revenue structure is also reported in order to evaluate the relative value of various products. A summary of bird suitability for all orders, a summary of the weight or number of pieces required to fill each order, and the degree to which each order was filled, cost, income and profit are summarized graphically for each order. The quantity of products ordered and the utilization of all carcass parts are also summarized graphically in order to balance supply with demand.

***Response analysis***

For any user-specified collection of orders, the sensitivity of profitability to strain, sex and market BW can be evaluated. Where constraints are placed on orders the optimum market BW range can be approximated in this way. Selected strains, sexes and BW combinations are simulated, generating a comparison of profitability for each scenario. In this way, profitability can be estimated for each genetic group over a range of market BW, and the genetic group and BW combination yielding the maximum profitability can be identified.

***Simulation experiment***

A simulation experiment was conducted to determine the best broiler strain cross for a mixed Value-added (V-A) market where a premium is obtained for white (breast) meat and a whole bird based market. Separate male and female broiler flocks from six strain crosses were simulated in the target market live BW range of 1.8 to 2.8 kg, at 0.1 kg increments. The six commercial strain crosses included in the analysis were Peterson x Arbor Acres Plus (PxA); Ross x Arbor Acres Plus (RxA); Cobb x Cobb 500 (CxC); Hubbard x Hubbard HI-Y (HxH); Ross x Hubbard HI-Y (RxH); and Ross x Ross 308 (RxR). These strains were used because growth and yield parameters have been developed for these strains from a trial conducted in the year 2000, and these strain crosses are representative of the range of birds grown in Alberta at the time. Although several years of further genetic progress have rendered this specific data no longer entirely pertinent for a contemporary strain decision, it was generated for this purpose, and it illustrates the powerful analytical potential of the model.

All monetary references are in Canadian dollars. Saleable chick costs were estimated for each strain using the hatching egg production cost module of BCSCM (Zuidhof, 2004a), based on data provided in the parent stock management guides of the respective breeding companies. Saleable chick costs for the RxA and RxH genotypes were not specifically included in that analysis. RxA and RxH saleable chick costs were estimated by combining the A and H female with the R male data reported in that analysis; PxA chick costs were estimated using the A female data, and using a lifetime feed intake and final BW of 50.0 kg and 4.5 kg, respectively, for the P male. Although chick cost estimates generated in this way may vary from commercial production costs, they demonstrate the ability of the model to incorporate hatching egg production data into an overall supply chain profitability-based strain decision. Strain-specific total chick costs were calculated as the sum of the saleable chick cost estimates, plus a fixed rate of $0.17 for hatchery costs. Strain-specific chick costs used in the current analysis were $0.514, $0.515, $0.508, $0.495, $0.496, and $0.528 for the PxA, RxA, CxC, HxH, RxH, and RxR strain crosses, respectively. To evaluate the effect of chick cost on profitability, both market scenarios were also evaluated with equivalent chick costs ($0.555/chick, the current commercial broiler price in Alberta). Broiler costs were simulated using the broiler module of BCSCM. A sample of the base broiler cost scenario is appended (Appendix 1).

Three years (2001 to 2003) of weekly Alberta retail product sales data (volume and dollar value) were obtained from ACNielsen[2]. These demand data were grouped into 52 products including whole bird and front half products (Table 3) and back half products (Table 4) and were used as the basis of the orders. For the whole bird scenario, only the products in the whole bird (first) column of Table 3 were used. For the V-A scenario, orders consisted of each of the products in the volume ratios

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[2]ACNielsen, 150 North Martingale Road, Schaumburg, IL 60173-2076 USA

reported in the table, scaled to a daily volume. Because the retail (V-A) scenario is not a complete picture of the market of a processing plant, many birds needed to be simulated in order to produce breast meat only, leaving other carcass parts with no value, biasing the economic results against the V-A scenario. Therefore a discounted price (15% less than the average wholesale price in Table 5) was assigned to surplus products resulting from the need to grow birds for breast muscle only.

The product prices reported in Tables 3 and 4 are retail prices. Wholesale prices were estimated from these prices. A composite retail-wholesale price spread from January 2003 to January 2004 (USDA, 2004) indicated that the average spread between wholesale and retail prices averaged 144% of the wholesale price. Therefore, a wholesale price was estimated using the equation $P_w = {P_r}/{1+1.44}$ where $P_w$ is the wholesale price, $P_r$ is the retail price, and 1.44 is the retail-wholesale price spread as a proportion of the wholesale price. These wholesale price estimates were used to assign value to the products produced in the simulations (Table 5).

Analyses were scaled to 80,000 kg/d, with a 5 d per wk plant operation schedule, for a total annual production volume of 20.857Mkg. Depreciation rates were set at 5, 10 and 15% for buildings, stationary equipment, and mobile equipment, respectively. Capital costs totaled \$9.86M, with a total annual depreciation of \$736,485. Fixed costs, variable costs and revenues are summarized in Table 6.

***Sex-separate market analysis.*** Because breast meat conformation differs substantially between males and females in most strains, different marketing strategies may be exploited to improve profitability. Using the Ross x Ross 308 bird as a model, three alternative sex-specific market strategies were evaluated according to the following scenario: an 80,000 kg market requires half of its birds for a whole bird market, and half for a value-added market, at 1.8 kg and 2.4 kg, respectively. Three strategies were investigated: 1) using mixed sex flocks, 2) channeling males to the value-added market, or 3) channeling females to the value-added market. A sexing cost of 2¢ per chick was used in the sex-separate scenarios.

Average profitability of males and females targeted to each market was established with and without sexing costs from six simulations. These values were multiplied by the number of birds required in each scenario and summed for an estimate of daily profit in each scenario. The percentage change was calculated for each scenario.

***Statistical analysis***

Carcass WOG yield estimates were determined using the MODEL procedure of SAS (SAS System, 2001) according to the procedure described by Zuidhof (2004c). Covariate analysis was conducted on the profitability data from the simulation using the MIXED procedure of SAS (SAS System, 2001). Strain and Sex were included as fixed effects, and the effect of BW on profitability was determined by including BW as a covariate. By replicating the BW variable and including it as a random class variable (Moser, 2004), with a first order autoregressive covariance structure, variation in strain-specific BW related changes in profitability was estimated appropriately. Including BW as a random effect decreased the BIC fit statistic, particularly for the whole bird market scenario.

***Results***

The results of the simulated experiment are summarized in Table 7. The ranking of profitability of strains with strain-specific and equivalent chick costs was similar. In order to simplify the discussion of the results the strain-specific scenarios are discussed in the following section. The difference between the strain-specific and equivalent chick cost scenarios represents the difference in margin that would accrue to hatching egg producers in scenarios where they are not paid according to strain.

The slope parameter associated with BW indicates that profitability increased significantly with BW in all scenarios. Profitability in the simulation increased at a rate of approximately $0.19 per kg of BW in the V-A scenario, and $0.14 per kg of BW in the whole bird market scenario. Figure 1 shows that the marginal effect of increasing BW on profitability (slope) decreased at higher market BW in the whole bird market scenario.

In the whole bird market scenario males were significantly more profitable than females by approximately $0.08/kg (Table 7). This effect was due to more rapid growth rates and lower carcass fat content, and was consistent at all BW (Figure 1). Because of higher breast meat yield, females were more profitable than males at low market BW in the V-A market scenario. In the V-A market scenario increased market BW improved profitability of males to a greater degree than females; by 2.5 kg profitability of males was equivalent to that of females (Figure 2). As females grew to larger BW, their efficiency was much poorer relative to males of corresponding BW. To summarize, females were more profitable in V-A markets at low BW, but not at higher BW.

There were no strain differences in profitability in the whole bird market (Table 7), where profitability was relatively low. In the V-A scenario where a premium was paid for breast meat, two strain crosses had superior profitability: those with the Hubbard HI-Y female parent (HxH and RxH; Table 7). Of the strain crosses evaluated, RxA was least profitable in the V-A market. Where the male parent (*i.e.* Ross male) was crossed with multiple strains there was a wide range of profitability outcomes, indicating either that the choice of the female parent may have a more significant effect on body conformation and therefore on profitability, or that the male lines contributed similarly to profitability. There was a significant Sex by Strain interaction in all market scenarios. In general, male broilers with a Hubbard HI-Y female parent were much more profitable than other male broilers, especially in the V-A market (Table 7). To a much smaller degree, the same was true for females.

***Sex separate market analysis.*** Results of the sex-separate market analysis are presented in Table 8. The model predicts that relative to a mixed-sex strategy (where males and females are grown together and channeled equally to value-added and whole bird markets), channeling females to the value-added market would result in an 11% increase in profitability. This is because increased value can be extracted from the advantageous breast meat conformation in females. Conversely, channeling males to the value-added market would decrease profitability by 20% relative to the mixed-sex strategy. This analysis accounts for a 2¢ per chick cost for sexing, but not for any advantages that might be gained from sex-specific nutritional programs (see Zoons et al., 1992). These results exploit sexual dimorphism in breast conformation, and the results of sex-specific marketing strategies would likely be less dramatic in the strains such as the Hubbard HI-Y crosses where male breast conformation is substantially improved.

### *Discussion*

In the whole bird market, profitability is largely a function of broiler production costs. As there is no premium in the whole bird market, the greatest amount of carcass weight at the same cost yields the highest profit. Males grow to market BW more efficiently than females and are therefore more profitable under this scenario. Profitability due to increased BW may reach a maximum and then decline if size or weight restrictions are imposed on the final product. Orders constrained by product size or weight limits are beyond the scope of the current analysis.

Where separate markets can be targeted by a processor, positive economic outcomes would result from growing males and females separately, and directing females toward the value-added markets, especially at market BW below 2.5 kg because of greater white meat yield (Zuidhof, 2004c) compared to males. In the North American marketplace, there is a premium for white meat, as reflected in the wholesale price estimates in Table 5. Males have a relatively higher market value than females at all BW in a whole bird market.

With a 4.57¢/kg range in profit between strains in the whole bird market, the strain decision for a processing plant producing 80,000 kg per day, five days per week represents a risk of $0.95M per year. The Strain decision is even more important in a V-A based market. With a range of 19.70¢/kg in value in the current analysis, the difference in profitability between the best and worst strains would be approximately $4.1M per year. Zuidhof (2004c) found that breast yield in the HxH and RxH males is substantially higher than in males of the other commercial strain crosses used in the simulation (Figure 4). The contribution of the Hubbard HI-Y female genetics, effectively makes the conformation of broiler males similar to females. Further, profitability of the high breast meat yielding male does not drop as quickly as in the female, improving the benefits in V-A markets (Figure 2).

Although the model takes many parameters into consideration, mortality was not considered in this analysis. Anecdotal reports from the Alberta broiler industry indicate that mortality in progeny of Hubbard HI-Y stock was higher. The sensitivity of supply chain profitability was therefore evaluated using the BCSCM. Under the conditions of the current analysis, a difference of 10% mortality affected live broiler margin by $0.047/kg live, and processing profitability by $0.0659/kg meat. In the whole bird market, this would eliminate the benefit of the Hubbard genetics. However, especially for males, there would be adequate advantage from the Hubbard genetics to be able to sustain the economic loss from 10% mortality under the V-A market scenario.

For models to support real-time decisions, strain- and sex-specific growth and yield data need to be developed in partnership with poultry breeding companies while strains are being developed. Quick and accurate feedback is the key to fine-tuning any system, and is a way for breeding companies to demonstrate the value of their genetic repertoire.

An integrated approach to the strain decision in the broiler supply chain lends great insight into optimal strain decisions. Consumer demand has a large influence on the optimal performance of the supply chain. Demand is dynamic. It is very important that a processor anticipate future demand in order to optimize Strain and market BW decisions. Demand forecasting, which is beyond the scope of the current study, will be an important consideration for decision makers.

*Acknowledgements*

The financial support of the project provided by the Alberta Agricultural Research Institute, the Alberta Chicken Producers, the Alberta Hatching Egg producers, and Lilydale Poultry Company is gratefully acknowledged.

Table 1. Nonlinear parameter estimates[1] for WOG[2] carcass weights. Data for males and females of six commercial strain crosses.

| Sex | Strain[3] | a | SEM | P | b | SEM | P |
|---|---|---|---|---|---|---|---|
| F | PxA | 58.661 | 2.9235 | <.0001 | 0.0229 | 0.0076 | 0.0080 |
| | RxA | 52.103 | 2.3611 | <.0001 | 0.0413 | 0.0068 | <.0001 |
| | CxC | 57.708 | 3.0979 | <.0001 | 0.0243 | 0.0081 | 0.0085 |
| | HxH | 58.652 | 1.9792 | <.0001 | 0.0237 | 0.0051 | 0.0002 |
| | RxH | 55.26 | 2.2999 | <.0001 | 0.0319 | 0.0062 | <.0001 |
| | RxR | 61.203 | 1.9697 | <.0001 | 0.0182 | 0.0049 | 0.0018 |
| M | PxA | 53.799 | 3.2971 | <.0001 | 0.0383 | 0.0086 | 0.0003 |
| | RxA | 54.629 | 2.3582 | <.0001 | 0.0369 | 0.006 | <.0001 |
| | CxC | 55.857 | 2.1865 | <.0001 | 0.0326 | 0.0054 | <.0001 |
| | HxH | 55.335 | 2.6375 | <.0001 | 0.0354 | 0.0066 | <.0001 |
| | RxH | 53.731 | 1.6207 | <.0001 | 0.0404 | 0.0042 | <.0001 |
| | RxR | 57.123 | 2.739 | <.0001 | 0.0306 | 0.0067 | 0.0002 |

[1]Estimates for the function $y=ax^b$ where $y$ is yield (%); $x$ is fat- and feather-free empty BW (g); and $a$ and $b$ are least squares estimated coefficients.

[2]WOG – chilled eviscerated carcass without neck, feet, or giblets.

[3]Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where male parent P = Petersen, R = Ross, C=Cobb, and H = Hubbard; and female parent A = Arbor Acres FSY; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 2. Equations used for the estimation of various carcass parts.

| Carcass part | Equation[1] | AdjF[2] |
|---|---|---|
| Back (no legs) | Back half – drums - thighs | |
| Drum skin[3] | N(0.07049,0.0296) + 0.000185 * skinless drums | |
| Drum bone[3] | N(0.2377,0.03386) + 0.00019 * skinless drums | |
| Drum meat | Skinless drums – drum bone | |
| Drums | Skinless drums + Drum skin | |
| Thigh skin[3] | N(0.1300,0.02673) - 0.00008 * skinless thigh | |
| Thigh bone[3] | N(0.2716,0.02839) + 0.00032 * skinless thigh | |
| Thigh meat | Skinless thigh + skin | |
| Front half | WOG - back half | |
| Front half (no wings) | Front half - wings | |
| Waste (P. Major)[4] | U(0,0.035) * P.Major | |
| Waste (P. Minor)[4] | U(0,0.050) * P.Minor | |
| Breast Bone[5] | U(0.100,0.125) * (P.Major+P.Minor) | |
| Breast Skin[5] | N(0.007,0.0002) * BW | |
| Other skin[6] | N(0.040,0.005) * BW | |
| Wing tips[5] | [N(0.1283,0.011) + AdjF] * wings | -0.0148 |
| Wing mids | N(0.3751,0.015) * wings | |
| Wing drummettes | Wings - wing tips - wing mids | |
| Blood (Morton et al., 1993) | BW * 0.06 | |
| Neck[5] | N(0.023,0.0035) * BW | |
| Feet | N(0.014,0.0007) * BW | |
| Shank | [N(0.025,0.003) + AdjF] * BW | -0.4498 |
| Bones | 0.250 * WOG | |

[1]Where coefficient mean $\mu$ and standard deviation $\sigma$ are presented in the format N($\mu$, $\sigma$), stochastic estimations were conducted using random draws of coefficients from the Normal distribution specified.

[2]AdjF is a coefficient adjustment factor to be applied where sex=F

[3]stochastic estimation constrained to within 1$\sigma$ of the mean

[4]stochastic estimation where coefficient is randomly drawn from a uniform distribution U(lower limit, upper limit)

[5]stochastic estimation constrained to within 3$\sigma$ of the mean

[6]stochastic estimation constrained to within 1$\sigma$ below the mean and 3$\sigma$ above the mean

Table 3. Mean weekly retail volume, annual value and retail price of whole broiler chickens, and broiler front-half products sold in Alberta from November 11, 2001 to November 29, 2003[1].

| | | Whole Carcass | | | Breast | | | Fillet | | | Wing | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type | Value added | Volume (kg/wk) | Value ($/yr) | Price ($/kg) | Volume (kg/wk) | Value ($/yr) | Price ($/kg) | Volume (kg/wk) | Value ($/yr) | Price ($/kg) | Volume (kg/wk) | Value ($/yr) | Price ($/kg) |
| Whole | None | 33,027 | 8,995,255 | 5.24 | 50,197 | 31,117,654 | 11.92 | 493 | 344,411 | 13.44 | 16,347 | 5,423,914 | 6.38 |
| | Frozen | 39,211 | 6,467,269 | 3.17 | 63 | 29,698 | 9.00 | | | | 86 | 19,994 | 4.46 |
| | Breaded | | | | | | | 121 | 101,670 | 16.15 | 12 | 9,113 | 15.23 |
| | Cooked | 27,211 | 9,380,478 | 6.63 | 867 | 236,795 | 5.25 | | | | 1,640 | 969,470 | 11.37 |
| | Cut | 15 | 4,387 | 5.65 | 199 | 98,303 | 9.48 | | | | 1,222 | 560,481 | 8.82 |
| | Marinated | | | | 189 | 133,961 | 13.67 | | | | | | |
| | Seasoned | 389 | 168,219 | 8.31 | 1,310 | 676,561 | 9.93 | 19 | 14,628 | 14.64 | 2,135 | 829,695 | 7.47 |
| | Stuffed | 7 | 2,067 | 5.71 | 10 | 7,041 | 14.08 | | | | | | |
| Boneless | None | | | | 775 | 673,039 | 16.70 | | | | | | |
| | Frozen | | | | 0 | 8 | 26.00 | | | | | | |
| | Seasoned | | | | 17 | 7,126 | 7.99 | | | | | | |
| | Stuffed | | | | 5 | 4,120 | 16.03 | | | | | | |
| Skinless | None | 212 | 104,487 | 9.48 | 2,964 | 1,418,463 | 9.20 | | | | | | |
| | Breaded | | | | 22 | 12,204 | 10.62 | | | | | | |
| | Cut | | | | 1,270 | 667,236 | 10.10 | | | | | | |
| Boneless-Skinless | None | | | | 43,754 | 30,081,348 | 13.22 | 235 | 220,492 | 18.05 | | | |
| | Frozen | | | | 3,217 | 1,696,772 | 10.14 | | | | | | |
| | Seasoned | | | | 18 | 12,642 | 13.83 | | | | | | |
| | Stuffed | | | | 0 | 408 | 16.97 | | | | | | |

[1]Source: ACNielsen, 150 North Martingale Road, Schaumburg, IL 60173-2076 USA

Table 4. Weekly volume, annual value and retail price of broiler back-half products sold in Alberta from November 11, 2001 to November 29, 2003[1].

| | | Legs | | | Thighs | | | Drums | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Type | Value added | Volume (kg/wk) | Value ($/yr) | Price ($/kg) | Volume (kg/wk) | Value ($/yr) | Price ($/kg) | Volume (kg/wk) | Value ($/yr) | Price ($/kg) |
| Whole | None | 21,006 | 3,129,997 | 2.87 | 37,056 | 9,855,279 | 5.11 | 37,186 | 8,615,957 | 4.46 |
| | Frozen | 170 | 89,985 | 10.20 | 82 | 15,317 | 3.61 | 60 | 8,293 | 2.65 |
| | Breaded | | | | 0 | 74 | 4.22 | | | |
| | Cooked | 1,114 | 142,691 | 2.46 | 506 | 43,882 | 1.67 | 468 | 46,886 | 1.93 |
| | Seasoned | 127 | 21,415 | 3.24 | 50 | 13,211 | 5.12 | 662 | 174,975 | 5.08 |
| | Stuffed | 0 | 25 | 5.43 | | | | | | |
| Boneless | None | | | | 206 | 137,194 | 12.81 | | | |
| Skinless | None | | | | 169 | 52,010 | 5.91 | 60 | 16,512 | 5.31 |
| | Seasoned | | | | 5 | 1,467 | 6.19 | | | |
| Boneless-skinless | None | | | | 5,388 | 2,618,998 | 9.35 | 14 | 8,007 | 11.35 |

[1]Source: ACNielsen, 150 North Martingale Road, Schaumburg, IL 60173-2076 USA

Table 5. Wholesale price estimates[1] for poultry products in processing simulation.

| Type | Value added | Whole carcass | Breast | Fillet | Wings | Legs | Thighs | Drums |
|---|---|---|---|---|---|---|---|---|
| | | ($/kg) | | | | | | |
| Whole | None | 2.15 | 4.89 | 5.51 | 2.62 | 1.17 | 2.10 | 1.83 |
| | Frozen | 1.30 | 3.69 | | 1.83 | 4.18 | 1.48 | 1.09 |
| | Breaded | | | 6.62 | 6.24 | | 1.73 | |
| | Cooked | 2.72 | 2.15 | | 4.66 | 1.01 | 0.68 | 0.79 |
| | Cut | 2.32 | 3.89 | | 3.62 | | | |
| | Marinated | | 5.60 | | | | | |
| | Seasoned | 3.41 | 4.07 | 6.00 | 3.06 | 1.33 | 2.10 | 2.08 |
| | Stuffed | 2.34 | 5.77 | | | 2.22 | | |
| Boneless | None | | 6.85 | | | | 5.25 | |
| | Frozen | | 10.66 | | | | | |
| | Seasoned | | 3.27 | | | | | |
| | Stuffed | | 6.57 | | | | | |
| Skinless | None | 3.89 | 3.77 | | | | 2.42 | 2.17 |
| | Breaded | | 4.35 | | | | | |
| | Cut | | 4.14 | | | | | |
| | Seasoned | | | | | | 2.54 | |
| Boneless-skinless | None | | 5.42 | 7.40 | | | 3.83 | 4.65 |
| | Frozen | | 4.16 | | | | | |
| | Seasoned | | 5.67 | | | | | |
| | Stuffed | | 6.96 | | | | | |

[1]based on a retail to wholesale price spread of 1.44

Table 6. Gross fixed and variable costs of production and gross revenues used in the simulation experiment.

| | Whole bird scenario | V-A scenario |
|---|---|---|
| Fixed costs | | |
| | ——— $/year ——— | ——— $/year ——— |
| Interest | 118,174 | 118,174 |
| Insurance | 145,000 | 145,000 |
| Taxes | 100,000 | 100,000 |
| Depreciation | 736,485 | 736,485 |
| Variable costs | | |
| | ——— $/day ——— | ——— $/day ——— |
| Labour | 13,500 | 13,500 |
| Other general costs | 9,350 | 9,350 |
| Secondary processing | 4,503 | 5,216 |
| Packaging | 3,132 | 7,119 |
| Revenue | | |
| | ——— $/day ——— | ——— $/day ——— |
| Value of product | 158,000 | 234,000 |

Table 7. Profitability of broiler meat production for males and females of six commercial strain crosses[1] for chicken produced for two processing scenarios, with simulated or constant chick prices.

| | | | Simulated chick cost | | Fixed chick cost | |
|---|---|---|---|---|---|---|
| BW | Sex | Strain cross | Value-added | Whole | Value-added | Whole |
| | | | Profit (CDN¢/kg per kg) | | | |
| Slope | | | 19.10 | 14.10 | 20.53 | 15.21 |
| SEM | | | 1.22 | 0.87 | 1.78 | 0.86 |
| | | | Profit (CDN¢/kg) | | | |
| | F | | 44.74$^{a}$ | 14.00$^{b}$ | 41.68$^{a}$ | 11.04$^{b}$ |
| | M | | 38.40$^{b}$ | 21.19$^{a}$ | 35.72$^{b}$ | 18.71$^{a}$ |
| SEM | | | 0.55 | 0.73 | 0.54 | 0.75 |
| | | PxA | 36.97$^{b}$ | 16.57 | 34.58$^{b}$ | 14.12 |
| | | RxA | 32.60$^{c}$ | 17.96 | 30.15$^{c}$ | 15.57 |
| | | CxC | 37.98$^{b}$ | 15.55 | 34.79$^{b}$ | 12.25 |
| | | HxH | 50.46$^{a}$ | 18.69 | 47.01$^{a}$ | 15.30 |
| | | RxH | 52.34$^{a}$ | 20.12 | 48.67$^{a}$ | 16.87 |
| | | RxR | 39.06$^{b}$ | 16.66 | 36.99$^{b}$ | 15.14 |
| SEM | | | 0.96 | 1.78 | 0.93 | 1.84 |
| | F | PxA | 44.11$^{cd}$ | 12.47$^{e}$ | 41.53$^{c}$ | 9.78$^{c}$ |
| | | RxA | 40.35$^{d}$ | 15.96$^{cde}$ | 37.61$^{d}$ | 13.14$^{bc}$ |
| | | CxC | 44.40$^{c}$ | 11.66$^{e}$ | 41.30$^{cd}$ | 8.17$^{c}$ |
| | | HxH | 44.80$^{c}$ | 14.65$^{e}$ | 41.15$^{cd}$ | 11.03$^{c}$ |
| | | RxH | 49.56$^{b}$ | 15.80$^{de}$ | 45.54$^{b}$ | 12.40$^{bc}$ |
| | | RxR | 45.20$^{c}$ | 13.46$^{e}$ | 42.95$^{bc}$ | 11.73$^{bc}$ |
| | M | PxA | 29.84$^{e}$ | 20.67$^{abc}$ | 27.63$^{e}$ | 18.47$^{a}$ |
| | | RxA | 24.85$^{f}$ | 19.97$^{abcd}$ | 22.70$^{f}$ | 18.01$^{a}$ |
| | | CxC | 31.56$^{e}$ | 19.44$^{bcd}$ | 28.28$^{e}$ | 16.33$^{ab}$ |
| | | HxH | 56.13$^{a}$ | 22.73$^{ab}$ | 52.88$^{a}$ | 19.57$^{a}$ |
| | | RxH | 55.13$^{a}$ | 24.44$^{a}$ | 51.81$^{a}$ | 21.33$^{a}$ |
| | | RxR | 32.92$^{e}$ | 19.86$^{abcd}$ | 31.04$^{e}$ | 18.54$^{a}$ |
| SEM | | | 1.36 | 1.79 | 1.32 | 1.85 |
| Effect | | | Prob > F | | | |
| BW | | | <.0001 | <.0001 | <.0001 | <.0001 |
| Sex | | | <.0001 | <.0001 | <.0001 | <.0001 |
| Strain | | | <.0001 | 0.5039 | <.0001 | 0.6123 |
| Sex*Strain | | | <.0001 | <.0001 | <.0001 | <.0001 |

[1]Strain crosses (year of study: 2000) are coded as follows: Male parent x Female parent where P = Peterson; A = Arbor Acres Classic; R = Ross 308; C = Cobb 500; H = Hubbard HI-Y.

Table 8. Profitability of three market scenarios where 1) males and females are grown as a mixed-sex flock and channeled equally to a value-added and whole bird market; or males and females are grown separately and 2) females are channeled to the value-added market and males to the whole bird market or 3) males are channeled to the value-added market and females to the whole bird market.

| | | Quantity required | | | | |
|---|---|---|---|---|---|---|
| Scenario | Market | Kg | Birds | Margin ($/kg) | Margin ($/d) | Change |
| 1: mixed sex flock | | | | | | |
| Males | V-A | 32,653 | 13,605 | 0.3678 | 12,011 | |
| Females | V-A | 32,653 | 13,605 | 0.4769 | 15,573 | |
| Males | Whole | 24,490 | 13,605 | 0.0876 | 2,145 | |
| Females | Whole | 24,490 | 13,605 | 0.0381 | 932 | |
| | | | | | 30,661 | 0% |
| 2: females for V-A | | | | | | |
| Males | V-A | - | - | 0.3562 | - | |
| Females | V-A | 65,306 | 27,211 | 0.4616 | 30,142 | |
| Males | Whole | 48,980 | 27,211 | 0.0770 | 3,770 | |
| Females | Whole | - | - | 0.0259 | - | |
| | | | | | 33,912 | 11% |
| 3: males for V-A | | | | | | |
| Males | V-A | 65,306 | 27,211 | 0.3562 | 23,262 | |
| Females | V-A | - | - | 0.4616 | - | |
| Males | Whole | - | - | 0.0770 | - | |
| Females | Whole | 48,980 | 27,211 | 0.0259 | 1,269 | |
| | | | | | 24,531 | -20% |

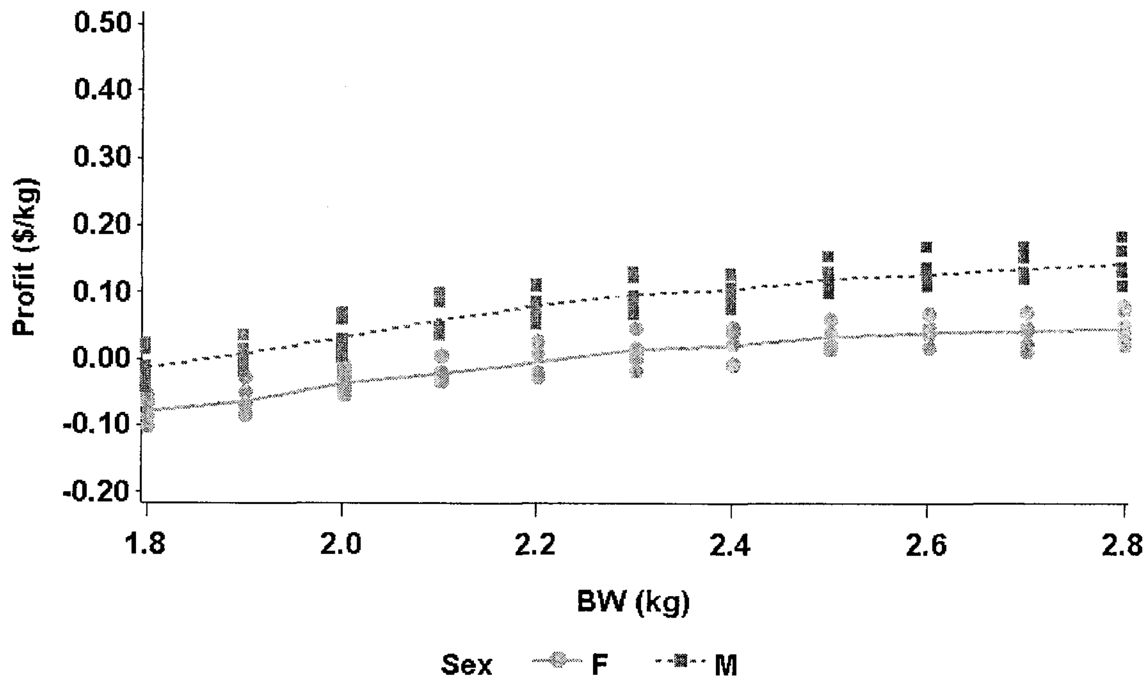


Figure 1. Effect of BW and sex on profitability of commercial broilers under a whole bird based processing scenario.

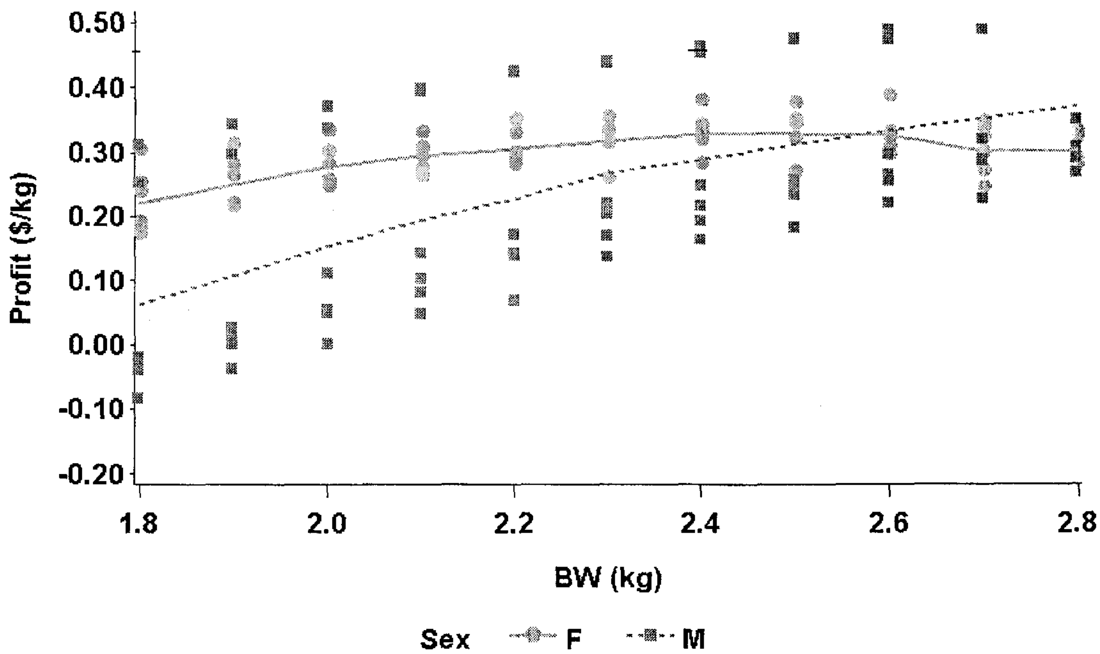


Figure 2. Effect of BW and sex on profitability of commercial broilers under a value-added processing scenario.

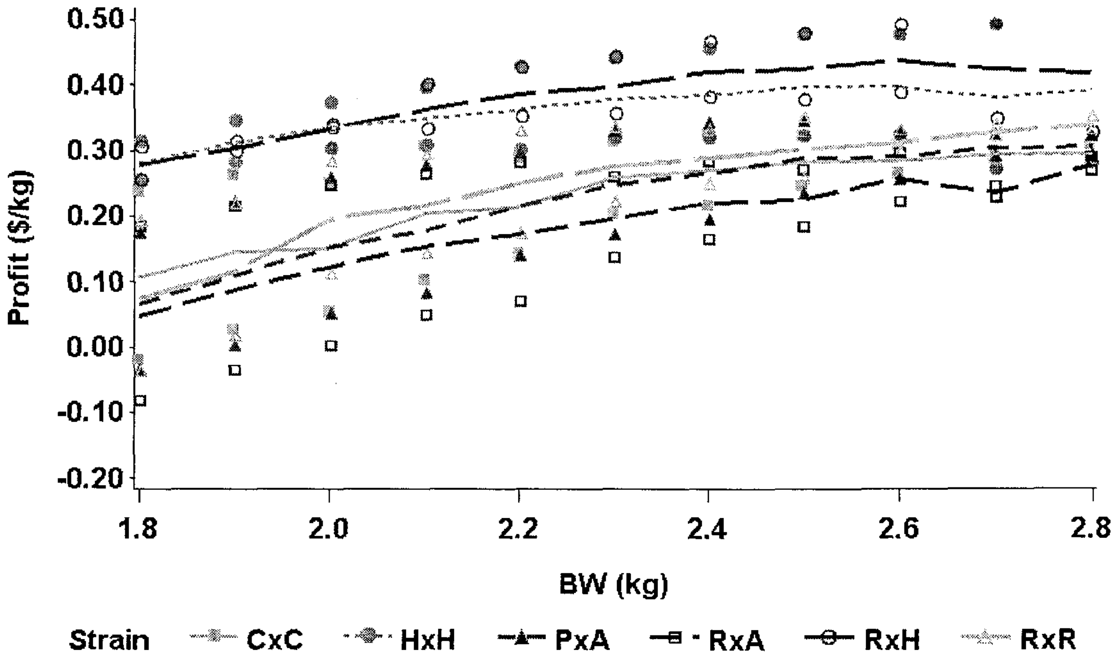


Figure 3. Effect of BW and strain on profitability of commercial broilers under a value-added processing scenario.

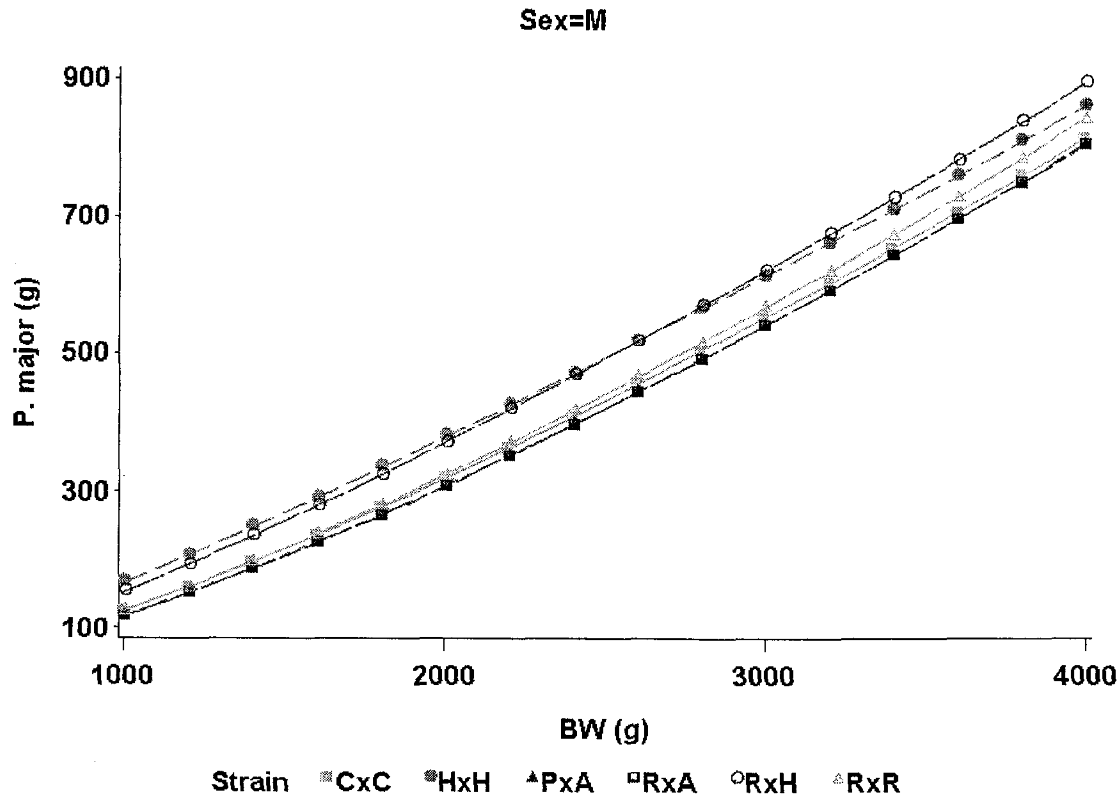


Figure 4. BW related *Pectoralis major* yield of males of six commercial strain crosses (adapted from Zuidhof, 2004c).

***References***

Morton, D. B., D. Abbot, R. Barclay, B. S. Close, R. Ewbank, D. Gask, M. Heath, S. Mattic, T. Poole, J. Seamer, J. Southee, A. Thompson, B. Trussell, C. West, and M. Jennings. 1993. Removal of blood from laboratory animals and birds. First report of the BVA/FRAME/RSPCA/UFAW joint working group on refinement. Laboratory Anim.s 27:1-22.

Moser, E. B. 2004. Repeated measures modeling with PROC MIXED. Proceedings of the Twenty-Ninth Annual SAS Users Group International Conference, Montreal, QC, Canada. SAS Institute, Inc.

SAS System, Version 8.02. Copyright © 1999-2001 by SAS Institute, Inc., Cary, NC, USA.

USDA. 2004. Historical monthly price spread data for beef, pork, broilers, turkeys, and eggs . http://www.ers.usda.gov/briefing/foodpricespreads/meatpricespreads/historicalspreaddata.xls; accessed July 16, 2004.

Zoons, J., E. Decuypere, and J. Buyse. 1992. Model based analysis of the profitability of sex separated broiler production. Landbouwtijdschrift-Revue De L Agric. 45:519-530.

Zuidhof, M. J. 2004a. A bioeconomic model of the broiler chicken supply chain. Chapter 3. A hatching egg production model. Ph.D. Thesis. University of Alberta.

Zuidhof, M. J. 2004b. A bioeconomic model of the broiler chicken supply chain. Chapter

4. A bioeconomic model of broiler chicken production. Ph.D. Thesis. University of Alberta.

Zuidhof, M. J. 2004c. A bioeconomic model of the broiler chicken supply chain. Chapter 5. Mathematical characterization of broiler carcass yield dynamics. Ph.D. Thesis. University of Alberta.

Appendix 1. Base broiler cost scenario used in the simulation experiment

## Broiler Chicken Economic Model

**Comments**

**Strains**

**Benchmarks**

| | | | |
|---|---|---|---|
| Placement date: 5/31/2004 | | Marketing date: 7/23/2004 | |
| Quota units (farm size) | 50,000 | Utilization factor (% of quota) | 99.800% |
| Quota leased in(out) (kg) | 0 | Conversion factor (kg/quota unit/wk) | 0.3700 |
| Chicks placed per cycle | 71,226 | Cycle length (wk) | 8 |
| Chicks paid for ( 2.0% free) | 69,829 | Cycles per year | 6.522 |
| Birds marketed per cycle | 70,335 | Bird age at marketing (days) | 53 |
| Live production per cycle (kg) | 147,704 | Mortality (%) | 0.0000% |
| Market weight (kg) | 2.1000 | Condemns(%) | 1.2500% |
| Live broiler price ($/kg) | 1.1980 | Chick weight (g) | 42.00 |
| Premium ($/kg) | 0.0000 | **Stocking Density** | |
| Barn space (sq ft) | 50,000 | sq ft/bird placed | 0.7020 |
| Barn cost ($/sq ft) | 11.0000 | sq ft/bird marketed | 0.7109 |
| Equipment cost ($/sq ft) | 4.3500 | kg marketed/sq ft | 2.9541 |

**Capital Costs**

| | |
|---|---|
| Land $1,000/acre | 20,000 |
| Building | 550,000 |
| Equipment | 217,500 |
| Shop | 10,000 |
| Mobile equipment | 10,000 |
| Quota $41.72/unit | 2,086,000 |
| Total Capital Costs | 2,893,500 |

**Feed Costs**

| | | Consumption (kg/bird) | $/tonne | $/bird |
|---|---|---|---|---|
| Feed conversion rate | 1.9500 | | | |
| Starter | | 0.20[illegible] | 318.00 | 0.06[illegible]6 |
| Grower | | 0.4[illegible] | 281.00 | 0.1[illegible]24 |
| Finisher | | [illegible]13 | 273.00 | 0.[illegible]496 |
| Finisher II | | [illegible].400 | 252.50 | [illegible].3535 |
| Other | | 0.000 | 252.50 | 0.0000 |
| Weighted feed cost | | | 268.89 | 1.0791 |

Simulated Simulated

**Fixed Costs**

| | Annual | $/cycle | $/kg |
|---|---|---|---|
| Money borrowed: $ 745,000 (25.75% of investment) | | | |
| **Loan payment** | 77,341 | 11,858 | 0.0803 |
| Principal portion | 23,328 | 3,577 | 0.0242 |
| Interest portion (@7.250%) | 54,013 | 8,281 | 0.0561 |
| Debt servicing ratio 3.497 | | | |
| Insurance | 5,800 | 889 | 0.0060 |
| Taxes | 6,150 | 943 | 0.0064 |
| **Depreciation** | 154,650 | 23,711 | 0.1605 |
| Building (10%/yr) | 56,000 | 8,586 | 0.0581 |
| Equipment (20%/yr) | 43,500 | 6,669 | 0.0452 |
| Mobile Equipment (30%/yr) | 3,000 | 460 | 0.0031 |
| Quota ( 2.50%/yr) | 52,150 | 7,996 | 0.0541 |
| Total Fixed Costs | 220,613 | 33,824 | 0.2290 |

Printed: 7/17/2004 File: 040713M.CO2

BCSCM version 2.46 page 1 of 2

| Variable Costs | $/unit | $/cycle | $/kg |
|---|---|---|---|
| Chick | 0.5550 | 38,755 | 0.2624 |
| Vaccination | 0.0000 | 0 | 0.0000 |
| Sexing | 0.0000 | 0 | 0.0000 |
| Feed | 268.89 | 76,858 | Simulated |
| Catching (per bird caught) | 0.0601 | 4,281 | 0.0290 |
| Utilities / Energy ($ / month) | 2,300 | 4,293 | 0.0291 |
| Labour (8.28 hours/flock/day) | 12.00 | 5,564 | 0.0377 |
| Repairs (0.8635% of capital costs) | 6,800 | 1,043 | 0.0071 |
| Veterinary | | 350 | 0.0024 |
| Litter | | 375 | 0.0025 |
| ACP levy | 0.0125 | 1,846 | 0.0125 |
| Quota leased in (out) 0 kg @ 0.0000 /kg | | 0 | 0.0000 |
| Market development quota 0 kg @ 0.0000 /kg | | 0 | 0.0000 |
| Miscellaneous | | 290 | 0.0020 |
| Total Variable Costs | | 133,655 | Simulated |
| **Summary of Costs and Returns** | **annual** | **$/cycle** | **$/kg** |
| **Summary of income** | | | |
| Base income (live production) | 1,154,121 | 176,949 | 1.1980 |
| Premium | 0 | 0 | 0.0000 |
| Miscellaneous | 0 | 0 | 0.0000 |
| Total income | 1,154,121 | 176,949 | 1.1980 |
| **Summary of expenses** | | | |
| Feed and chick cost | 754,064 | 115,613 | Simulated |
| Other variable costs | 117,676 | 18,042 | 0.1221 |
| Total fixed costs | 220,613 | 33,824 | 0.2290 |
| Total expenses | 1,092,353 | 167,479 | Simulated |
| **Margins** | | | |
| Over feed and chick | 400,056 | 61,338 | 0.4153 |
| Over total variable costs | 282,380 | 43,294 | 0.2931 |
| Over all costs (net return) | 61,768 | 9,4[illegible] | [illegible]41 |
| Cash flow (before loan principal payment) | 216[illegible] | [illegible] | 0.2246 |
| Cash flow (after loan principal payment) | [illegible] | 29,604 | 0.2004 |
| Break even for all cash outlays | [illegible] | 147,345 | 0.9976 |
| Break even income | | | 1.1339 |
| Gross income | | | 1.1980 |
| **Net Return** | | | |
| (per bird shipped) | | $0.1346 | |
| (per [illegible]pped) | | | $0.0641 |
| ([illegible] paid for) | | | $0.0641 |
| (per square foot) | | | $0.1894 |

Simulated

Printed: 7/17/2004 File: 040713M.CO2

BCSCM version 2.46 page 2 of 2

# CHAPTER 7. BIOECONOMIC MODELING: IMPLICATIONS FOR THE BROILER CHICKEN SUPPLY CHAIN


## *Abstract*

A bioeconomic model was applied to the complex strain decision in the broiler chicken supply chain (SC). Through a sensitivity analysis, economically equivalent production parameters in the broiler and broiler breeder sectors were identified. Through multiple simulations of strain performance over a market BW range of 1.8 to 2.9 kg, strain-specific chick cost and profitability relationships were elucidated. Tradeoff analyses were used to identify the optimal strain choice. Generally, in a value-added and in a whole bird market, the RxH strain was identified as optimal. Similar, but slightly reduced performance was estimated for the HxH strain. Constrained analysis demonstrated the ability of the model to identify market-specific optimal harvesting BW. Some caveats and recommendations were identified to improve relevance in commercial applications of the model. This analysis suggests that a bioeconomic model can be used to provide tremendous insights that could support the strain decision in a broiler SC.


Abbreviation key: FCR = feed conversion ratio; HH = hen housed; SC = supply chain; V-A = value-added

## *Introduction*

Profitability is a natural performance indicator for business. Within a supply chain (SC), however, it is often not possible to simultaneously maximize individual and overall profitability. The hatching egg industry has been aware for decades that they face economic disadvantage with some modern strains. Cumulative performance improvements in broiler traits over decades aimed at improving SC profitability have compounded reproductive problems faced by breeder hens. An initial response to the tradeoff, one that is now firmly entrenched in modern breeder management, was to manage parent stock differently. Reports in the scientific literature as early as 1959 (Sherwood, 1959) identified benefits of restricting feed intake of meat-type chicken parent stocks. Preventing parent stocks from expressing their growth potential through controlled feed intake has enabled the hatching egg sector to cope economically for almost 50 years. Staggering changes in broiler traits, however, have forced breeding companies to alter selection programs to include egg production traits. Hybrid crosses of separate male lines selected for growth, efficiency and yield with female lines selected to a greater extent for egg production traits, is standard industry practice. Inevitably however, egg production traits have been compromised. Chick costs have increased in part due to maintenance requirements on heavier parent stock frames, but mostly due to reduced egg and chick output. Incremental cost increases are modest at high production rates, but there is an exponential increase in per-chick production costs as chick numbers decrease. Every decrease of one chick per hen puts more economic pressure on hatching egg producers than the previous chick (see Figure 1).

Economic benefits of greater yield at younger ages have completely overshadowed the cost of reproductive dysfunction. As such, there is a notable gap in the scientific literature on the economic tradeoff between broiler traits and reproductive performance of parent stocks. In one of the few papers on the subject, Carte (1986) identified levels of productivity throughout the supply chain (SC) such as egg production, feed conversion rates and meat yield with equivalent impact on meat value. In 1986, he estimated that 29 chicks per breeder hen was equivalent economically to an increase in carcass weight of 0.40 lbs (182 g) or a yield improvement of 1%. At the time, Carte concluded that the economic value of broiler traits was so much greater than that of breeder traits that a full selection emphasis on broiler traits was justified. Recently, the broiler breeder industry has come to a crisis regarding the profitability of some strains (Mussell[1], personal communication). It is worthwhile to revisit Carte's estimates after almost another two decades of selection.

***Tradeoff analysis***

For the broiler chicken SC, alternative strain crosses represent an array of choices which trade off processing value with reproduction. Tradeoff analysis (Shapiro, 2001 p. 9; Stoorvogel et al., 2004) is a means of evaluating alternative scenarios. In order to aid investors in the portfolio selection decision, Markowitz (1952) developed the concept of risk efficiency analysis, a means of determining the relative worth of alternative scenarios by simultaneously examining expected reward with variability of the expected outcome. Figure 2 contains a modified theoretical risk efficiency plot. Risk (variance in expected outcome) is plotted on the x-axis, and reward (highest expected return) is plotted on the y-axis. Scenarios that fall into the lower right hand quadrant are high risk scenarios with low expected returns. Scenarios that fall into the upper left quadrant have lower risk, and higher expected returns. These scenarios are preferred, and are considered to have high risk efficiency.

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[1] Allan Mussel, George Morris Centre, Guelph ON.

Like variability in expected outcome, the cost of producing hatching eggs comprises a type of risk for the chicken meat SC. The reward or benefit extracted from a strain choice can be evaluated in terms of SC profitability. In the chicken supply chain then, chick cost (as a proportion of the cost of producing chicken meat) can be plotted on the risk or x-axis. SC margin or profit ($revenue - cost$) can be plotted on the reward or y-axis. Scenarios that fall in the lower right quadrant have low risk efficiency, where increased risk (chick cost) does not result in higher reward (SC profitability). Preferred scenarios fall in the upper left quadrant, where higher profitability is achieved with lower input (chick) costs. The risk efficiency frontier is comprised from the highest reward and lowest risk scenarios (Perillat et al., 2004). Risk efficiency analysis aids the decision process through identification of risk efficient scenarios. In this respect, the current analysis is similar to risk efficiency and tradeoff analyses.

### *Objectives*

The objectives of the current analysis are to 1) determine the level of broiler and breeder production traits with equivalent economic significance; and using risk efficiency analysis, to 2) evaluate the economic implications of alternative strain choices; 3) evaluate the economic importance of market weight for SC economics; and 4) to identify the best strain choice for the broiler SC.

### *Approach*

***Economic equivalencies.*** An array of equivalent broiler and breeder production parameters (Carte, 1986) was determined through sensitivity analysis using a bioeconomic model of the broiler chicken SC. Broiler production variables that Carte analyzed were broiler BW, feed conversion ratio (FCR), processing yield, percent condemnations, and percent livability. Total live production cost and chick cost were added to the current analysis, since these variables are particularly helpful for thinking about economics from a SC perspective. The number of saleable chicks per hen housed (HH) was added to the breeder variables analyzed by Carte: hatching eggs/HH, hatchability, feed/doz eggs, cost/doz eggs, and feed/HH. Values from Carte (1986) were adjusted by an inflation index of 1.71 (1986 value of 2004 dollars; Federal Reserve Bank of Minneapolis, 2004). Eight broiler scenarios were evaluated: 2.0 and 2.5 kg female and male Ross x Ross 308 broilers in two market scenarios: whole bird and value-added (V-A). Breeder parameter values were estimated at two levels of production: 130 and 100 chicks per hen housed. All monetary references are in Canadian dollars.

***Risk efficiency analysis.*** An array of simulations was conducted using the broiler chicken SC model to evaluate alternative strain choices. For two market scenarios (whole bird and V-A), the economic values (net margin) of females and males of six commercial strain crosses were determined through simulation. Simulations were conducted over a target market BW range of 1.8 to 2.8 kg in 0.1 kg increments. Using the chick cost component of total cost of the final products as a measure of risk, and the profitability of each scenario as a measure of reward, a risk efficiency analysis was performed. To demonstrate the effect of product size constraints on optimal performance, a V-A market scenario was conducted with male HxR broilers using size constraints of 1.4 to 1.6 kg for 99% of the whole chicken products. In the constrained analysis, a market BW range of 1.8 to 2.4 kg was used, in 0.02 kg increments of target market BW.

### *Results and discussion*

***Economic equivalencies.*** Breeder and broiler production traits that result in equivalent net changes in profitability (1¢/kg meat) are summarized in Table 1. Carte (1986) evaluated broilers at 6 wk of age, and breeders at 280 d of production. The lighter broiler (2.0 kg) BW scenarios most closely match Carte's scenario. The 130 chick scenario is the closest match to Carte's breeder scenario.

*Broiler traits.* The sensitivity of SC profitability to live BW has approximately doubled since 1986 (only half of the estimated live BW difference in 1986 is now required to achieve a 1¢ change in meat value). Sensitivity decreases as BW increases (it takes a larger change in BW at 2.5 kg than at 2.0 kg to effect a 1¢/kg change in meat value). Sensitivity to FCR has remained about the same. In 1986, smaller (0.58%) changes in processing yield were required to bring about a 1¢/kg change in market value. Reduced sensitivity to changes in yield is due to increased BW; a smaller percentage change in yield is now required to effect an equivalent absolute change in yield weight. The relative effect of improved yield on SC profitability is independent of sex, target market BW and market type (see Figure 3).

To bring about a 1¢/kg change in meat value, Carte reported lower values of condemnations and mortality than current estimates. It is possible that these values have been calculated differently. In the current analysis, the model adjusts chick placements to compensate for mortality and condemnation in order to compare equivalent scenarios (always the same number of kg marketed). This approach decreases sensitivity to condemnations and mortality. This approach is justified because systematic (truly strain-specific) mortality and condemnations would require adjustments in chick placements to compensate for a reduction in marketable weight.

Total changes in live costs that result in a 1¢/kg change in meat value range from 0.70 to 0.73 ¢/kg. This is equivalent to a change in chick price of 1.47 to 1.53¢/chick for females; 1.78 to 1.88¢/chick for males. Equivalencies generally were more sensitive in females because of smaller BW compared to males. Equivalencies were similar in the whole bird and V-A marketplace.

*Breeder traits.* Equivalent sensitivities of meat value to breeder production traits are summarized in Table 1. Two main effects are evident. First, a 1¢/kg change in meat value is less sensitive to chick costs at higher broiler market BW. This is due to the meat-to-chick ratio. When broilers are grown to larger market BW fewer chicks are required to produce an equivalent amount of meat. Second, sensitivity of meat value to breeder production parameters is higher at low chick production levels; equivalent impacts on meat value are effected with smaller changes in breeder production parameters at low chick production rates than at high rates. Since total production costs are relatively consistent on a per-hen basis, decreasing chick output increases the cost per chick (see Figure 1).

Over time, increases in feed cost have been offset by improvements in broiler efficiency. Presumably because feed costs have not changed dramatically, the influence of feed cost (per dozen hatching eggs) at the broiler breeder level has not changed dramatically since Carte's 1986 estimates. At production levels of 130 chicks per HH, meat value is slightly less sensitive to breeder feed cost (per HH) than in 1986. This difference may be due to improved feed conversion efficiency resulting from selection for broiler traits. At 100 chicks per HH, sensitivities of meat value to breeder performance traits are greater than those reported by Carte. Comparison of the 2.0 kg and 2.5 kg broiler BW scenarios demonstrates that efficiencies gained through higher market BW reduce the influence of breeder feed on meat production costs. The magnitude of the effect of breeder feed cost on meat value is comparable to the ratio of the increase in broiler market BW.

Meat value is less sensitive to the total cost per dozen eggs than in 1986 because of improved broiler performance. Meat value is much more sensitive to hatching egg numbers and hatchability than in 1986. As egg numbers decrease, breeder productivity parameters that translate directly into chicks per HH become much more important for the chicken SC. Carte (1986) warned that as egg costs increase due to selection for broiler traits the industry may be forced to emphasize breeder traits. After an additional 18 years of progress, there is solid evidence that reproductive traits are becoming more important economically.

***Risk efficiency analysis.*** The tradeoff between the chick proportion of meat production costs and net margin for the SC (profitability) is summarized for males and females in a market BW range of 1.8 to 2.8 kg in a whole bird market scenario (Figure 4), and a V-A market scenario (Figure 5). Chick cost as a proportion of total meat production costs decreases with increasing market BW because of higher meat:chick ratios (see Figure 6). Thus, in the risk efficiency plots, BW increases from right to left on the x-axis (chick cost). Clearly, from a reproduction / growth efficiency tradeoff perspective, an appropriate broiler SC strategy would be to market broilers at higher BW. However, this is not always possible due to market constraints. Using this tradeoff analysis as a decision aid, the strains on the risk efficiency frontier (farthest toward the upper left quadrant) would be a preferable for the SC, maximizing profitability with the least risk. In both the whole bird and V-A market scenarios the RxH strain cross has the greatest degree of clustering near the risk efficiency frontier, and would therefore be the best strain choice.

It is helpful to isolate scenarios of interest to elucidate patterns. In Figure 7, risk efficiency plots are presented separately for two strain crosses. The RxH risk efficiency frontier is higher than the RxR risk efficiency frontier. In the V-A market scenario, the profitability of males in both strains increases dramatically with increasing BW. However, the profitability of the RxH males is far superior to that of the RxR males. The risk efficiency frontier for females is lower that for males. Although profitability of females is relatively high at low BW (higher chick cost), it reaches a plateau because females approach their mature BW earlier than males. To evaluate the strain choice at lower BW, BW ranges can be compared separately. In Figure 8, three risk efficiency frontiers are charted, for three market BW categories. In each case the RxH and HxH strain crosses are on the risk efficiency frontier, and therefore represent the best choices for the SC. There is greater separation between strains at higher BW. The result of a constrained V-A market scenario is pictured in Figure 9. In contrast with the unconstrained analyses, there is a point where increased risk (chick cost) results in increased profitability. The imposition of constraints that reflect commercial product arrays enable company-specific optimal market BW and strain choices to be identified.

***What is the best strain choice?*** The risk efficiency analysis clearly identified two preferred strain crosses: the RxH and the HxH strains. These strain choices are preferred for both the V-A and the whole bird scenarios. Greater separation in profitability made the strain decision for the V-A market scenario much clearer than for the whole bird market.

***How confident can we be in the decision?*** There are four caveats to consider before implementing the strain decision identified by this analysis. First, the best decisions are made by minimizing the length of time between data collection and decision. Because of the time required to develop the model, the data collection phase preceded the conclusions by four years. Genetic progress at a rate greater than 3% per year in some traits reduces the degree of confidence in these results substantially. Having a model in place will allow the next phase of the decision process to proceed much more quickly.

Second, broiler mortality was not considered in this analysis. Commercially, one strain crosses with a Hubbard HI-Y maternal parent have had high mortality in the broiler barn. In whole bird markets, there may not be enough advantage to offset higher mortality rates. In a V-A market scenario, increased profitability due to breast meat yield, particularly in male broilers, will offset mortality rates in excess of 10% (see Zuidhof, 2004). When deciding in favour of a strain with high broiler mortality, concessions to broiler producers should be part of an implementation plan.

Third, performance data from breeder management guides were used to model hatching egg production costs. Typically such performance benchmarks represent top quartile or higher performance, and may not be realistic for the industry as a whole.

Breeder performance levels used in this analysis should be reevaluated for achievability.

Finally, the strain choice identified in the current analysis was conducted without product size or weight constraints. In order for an optimization to be relevant, the simulation must realistically reflect the market requirements. Product constraints affect the outcome of the analysis, particularly with regard to target market BW (Figure 9). There may also be strain-specific effects. Use of a bioeconomic model in a strain decision should include company-specific market scenarios.

***Should the SC compensate hatching egg producers for reduced performance?*** Based on the current analysis, the preferred strain choices (with the Hubbard HI-Y maternal parent) would not require extra compensation. As mentioned already, breeder data used in the analysis were from management guidelines, and may not be commercially applicable. Hatching egg production costs should be verified.

With the model described in this thesis, and the approach taken in the current analysis, cost equivalencies can be used to determine the relative value of alternative breeding stock for the broiler chicken SC. The level of compensation for strains with marginal reproductive traits should be based on commercial SC performance. SC profits should accrue to each sector based on the level of investment.

***Issues for compensating broiler growers.*** Two main performance-dependent factors should govern strain-specific compensation of broiler growers. Strain-specific differences in mortality, susceptibility to disease or metabolic disorders should be determined, and evaluated in the payment protocol. Second, improved growth rates are likely to accrue benefits to the broiler grower. These may offset or partially offset problems due to mortality or disease.

***Other tactical implications for the SC.*** Other implications emerged from the analysis. In some strain crosses there are clear sex differences in terms of their profitability in various markets. Sex separate growing is easily implemented, especially with feather-sexable strains. There are potential benefits in terms of growing efficiencies (Zoons et al., 1992), as well as processing line efficiencies, and perhaps even sex-specific product streaming. The economics of each specific scenario would need to be evaluated to determine the optimal strategy.

### *Summary*

The broiler chicken SC model developed in this thesis is a decision tool targeted at a management level. It is broad in scope, capturing important biological and economic elements of hatching egg production, broiler production, and processing, with particular attention to dynamic aspects of broiler conformation. It is particularly suited for evaluating the economic consequences of the strain decision. Though it is not particularly suited for operational level decisions in its current state, modules pertaining to various cost- or revenue-influencing factors could be developed and incorporated into it. Because the primary raw material in the chicken meat supply chain is biological, the stochastic nature of the model is particularly useful for decision support. Through analysis of multiple simulations of specific scenarios, the likelihood of achieving specific outcomes can be inferred. By helping the user to understand the risk associated with the complex strain decision, the model is a valuable decision support tool.

Real-time strain-specific data are required to enhance the value of this type of analysis for commercial strain decisions. Minimizing feedback time in complex decision processes is a critical success factor, particularly with biological systems. Cooperation with breeding companies to develop strain-specific data on parent stock reproductive traits and broiler performance and yield traits will be vital to successful application of this model. To be commercially relevant, strain-specific data development should occur early in the process of strain development. The use of temporally relevant data in a system analysis such as this is necessary to support optimal commercial decisions. In the broiler chicken SC, the strain decision is a complex problem. This analysis demonstrates that a bioeconomic SC model can be used to effectively support such a decision.

***Conclusions***

Systems models, though they embody powerful potential as decision support tools, have been difficult to implement in agriculture (McCown, 2001). The success of models should be judged by more than the level of implementation (*e.g.* number of users) alone. Levins (1966) wrote:

> *'A mathematical model is neither a hypothesis nor a theory. Unlike the scientific hypothesis, a model is not verifiable directly by an experiment. For all models are both true and false... The validation of a model is not that it is "true" but that it generates good testable hypotheses relevant to important problems.'*

Several relevant and testable hypotheses have emerged through the use of the current bioeconomic model of the broiler chicken SC. They include:

1. The maternal Hubbard HI-Y parent contributes large conformational improvements, particularly increased breast meat yield. This contribution increases SC profitability substantially in markets where a premium can be extracted for breast meat.
2. Contrary to the hypothesis that reproduction trades off with broiler traits, the RxH and HxH strain crosses were the most profitable for the supply chain, and achieve this with the greatest profitability at the hatching egg level.
3. An increase in broiler yield of 0.70 to 0.80% will result in a net increase in SC margin of $0.01/kg.
4. The contribution of commercially available males to the profitability of strain crosses is very similar.
5. Male broilers, by growing to equivalent market BW more efficiently than females, are more profitable in whole bird markets where no premium is extracted for conformational traits such as white (breast) meat.
6. Since a premium can be extracted for increased breast meat in V-A markets. In this type of market, female broilers at equivalent BW are more profitable than males, particularly at low BW.
7. Strains selected for breast meat yield are not particularly advantageous in whole bird markets.
8. When processors have access to varied markets, there may be economic advantages to growing and processing males and females separately.

Particularly at low to moderate BW, Males should be used for whole bird markets, and females should be targeted toward further processed markets.

***Reflections***

In order for agricultural SCs to maintain or improve their competitive position in the global marketplace, intuition alone is no longer a valid basis for decisions. Models that incorporate a diversity of variables ranging from equipment, production, and processing costs to the value of potential products are technologies of increasing importance. The bioeconomic model developed in this thesis is a framework that can improve the way broiler chicken SCs approach decisions. With continuous updating of broiler performance parameters, this framework will allow decision-makers in the broiler SC to make important economic decisions about the best economic strain choice with little knowledge or data on how male and female broilers of various strains grow. Through seamless incorporation of complex dynamic yield expectations, insights into alternative marketing strategies such as channeling sexes to different potential markets can be found. The effects of compromises or improvements in various sectors can be determined on overall profitability, enabling the SC as a whole to make better economic decisions. Elucidating the tradeoffs between sectors will improve trust along the SC, since negotiation of the best strain decision or production strategy will have completely incorporated the economic impact in each SC sector.

The model described in this thesis represents a significant advancement in SC decision technology. Still, there is room for development and improvement of the system dynamics. The cost of feeding is a substantial contributor to the overall cost of production, and to the market value of broiler carcasses. Broiler nutrition is a highly complex and variable science. Incorporation of ongoing advancements in this area will undoubtedly improve the value of this model for industry decisions.

Development of strain- and sex-specific responses to nutrient intake is needed. This work should be explored in conjunction with breeding companies as new broiler products are being developed in order to capitalize on information as new strains are released to industry. This work is expensive, as it usually involves many levels of nutrient intakes, and expensive laboratory analyses and labour-intensive carcass dissections. Substantial investment in the development of such data is easily justified. The benefits of this model are two-fold. First, a SC can reduce its exposure to economic risk by identifying the best strain. In this thesis, the difference in economic potential between the most and least appropriate strains totaled \$4.1M for a single modest sized processing plant utilizing a V-A market scenario. Second, because of the complexity of the broiler chicken SC, inefficiencies remain that offer tremendous opportunities for process improvement. Improvement of these areas of inefficiency will reap large economic rewards. Sex-separate marketing of broilers is one such efficiency. The model predicts that the benefits of this approach could total well over \$1M/yr for a small processing plant producing around 20M kg per year.

A bioeconomic model of the broiler chicken supply chain is a means of moving beyond cost accounting toward profit-based decision making. Continued development of the robust and flexible model developed in this thesis will undoubtedly increase the competitive edge of supply chains which choose to implement this technology.

Table 1. Production traits with equivalent impact on supply chain margin. For each scenario, the level of each production parameter results in an equivalent net margin of 1¢/kg meat. Data are summarized for females and males of the Ross x Ross 308 strain cross in retail (value-added) and whole bird market scenarios. Adapted values from Carte (1986) are also shown.

| | | Value added scenario | | | | Whole bird scenario | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Females | | Males | | Females | | Males | |
| Parameter | Carte 1986[1] | 2.0 kg | 2.5 kg | 2.0 kg | 2.5 kg | 2.0 kg | 2.5 kg | 2.0 kg | 2.5 kg |
| Broiler traits | | | | | | | | | |
| Live BW (kg) | 0.106 | 0.040 | 0.061 | 0.043 | 0.065 | 0.040 | 0.062 | 0.042 | 0.066 |
| FCR (g feed/g gain) | 0.029 | 0.026 | 0.026 | 0.027 | 0.027 | 0.026 | 0.026 | 0.027 | 0.026 |
| Processing yield (%) | 0.58 | 0.69 | 0.72 | 0.76 | 0.70 | 0.67 | 0.80 | 0.87 | 0.68 |
| Condemnations (%) | 0.70 | 0.89 | 0.91 | 0.94 | 0.98 | 0.89 | 0.92 | 0.94 | 0.96 |
| Liveability (%) | 1.29 | 2.25 | 2.78 | 2.35 | 2.88 | 2.23 | 2.78 | 2.33 | 2.91 |
| Live cost (c/kg) | - | 0.70 | 0.70 | 0.73 | 0.73 | 0.70 | 0.71 | 0.72 | 0.72 |
| Chick cost (c/chick) | - | 1.47 | 1.78 | 1.53 | 1.88 | 1.47 | 1.80 | 1.53 | 1.85 |
| Parent traits @ 130 chicks/HH | | | | | | | | | |
| Saleable chicks/HH | - | 5.9 | 7.1 | 6.1 | 7.5 | 5.9 | 7.2 | 6.1 | 7.4 |
| Hatching eggs/HH | 17.0 | 6.9 | 8.3 | 7.1 | 8.8 | 6.9 | 8.4 | 7.1 | 8.6 |
| Hatchability (%) | 9.4 | 3.9 | 4.7 | 4.0 | 5.0 | 3.9 | 4.8 | 4.0 | 4.9 |
| Feed (kg/doz eggs) | 0.69 | 0.65 | 0.78 | 0.67 | 0.83 | 0.65 | 0.79 | 0.67 | 0.81 |
| Feed (kg/HH) | 7.7 | 8.2 | 9.9 | 8.5 | 10.5 | 8.2 | 10.0 | 8.5 | 10.3 |
| Cost (c/doz eggs) | 9.4 | 18.6 | 22.5 | 19.3 | 23.7 | 18.6 | 22.7 | 19.3 | 23.4 |
| Parent traits @ 100 chicks/HH | | | | | | | | | |
| Saleable chicks/HH | - | 3.5 | 4.2 | 3.6 | 4.5 | 3.5 | 4.3 | 3.6 | 4.4 |
| Hatching eggs/HH | 17.0 | 4.1 | 4.9 | 4.2 | 5.2 | 4.1 | 5.0 | 4.2 | 5.1 |
| Hatchability (%) | 9.4 | 3.0 | 3.6 | 3.1 | 3.8 | 3.0 | 3.7 | 3.1 | 3.8 |
| Feed (kg/doz eggs) | 0.69 | 0.65 | 0.78 | 0.67 | 0.83 | 0.65 | 0.79 | 0.67 | 0.81 |
| Feed (kg/HH) | 7.7 | 6.3 | 7.6 | 6.5 | 8.0 | 6.3 | 7.7 | 6.5 | 7.9 |
| Cost (c/doz eggs) | 9.4 | 14.3 | 17.3 | 14.9 | 18.3 | 14.3 | 17.5 | 14.9 | 18.0 |

[1]To adjust for inflation between 1986 and 2004, 1986 values have been adjusted downward by a factor of 1.71 (Federal Reserve Bank of Minneapolis, 2004).

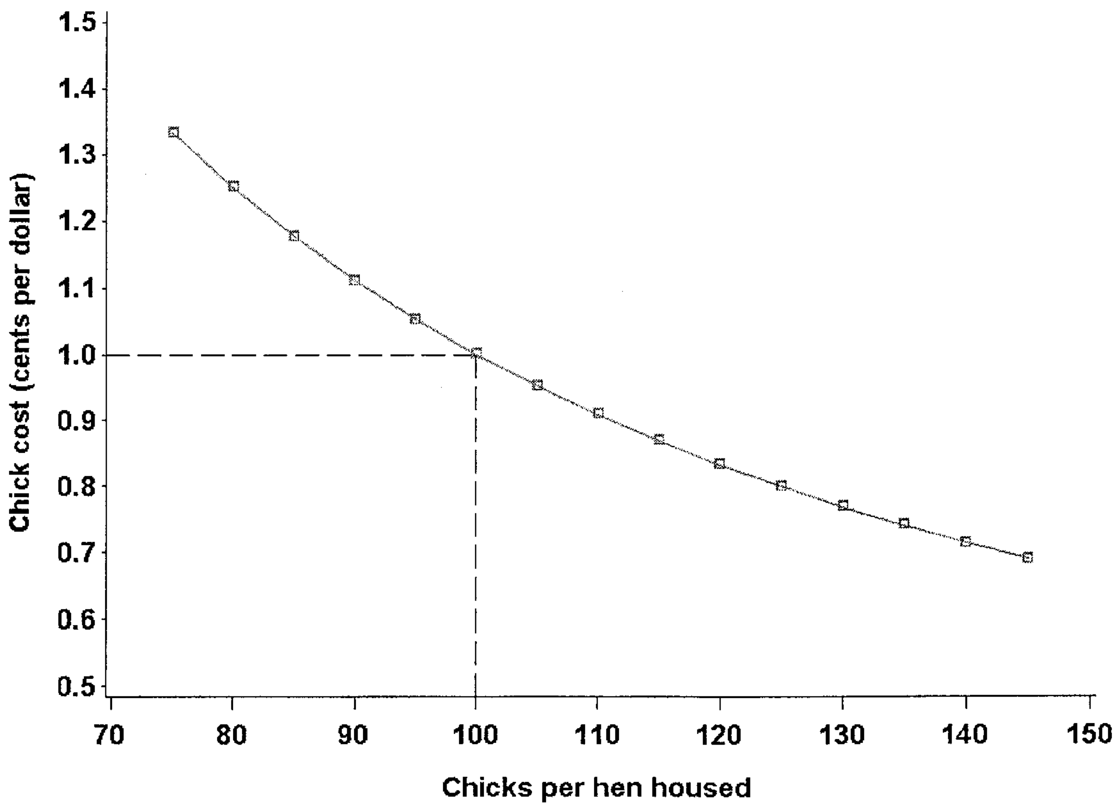


Figure 1. Per-chick costs increase exponentially with decreasing chick output. At a production level of 100 chicks per hen, one cent of every dollar spent per hen accrues to each chick.

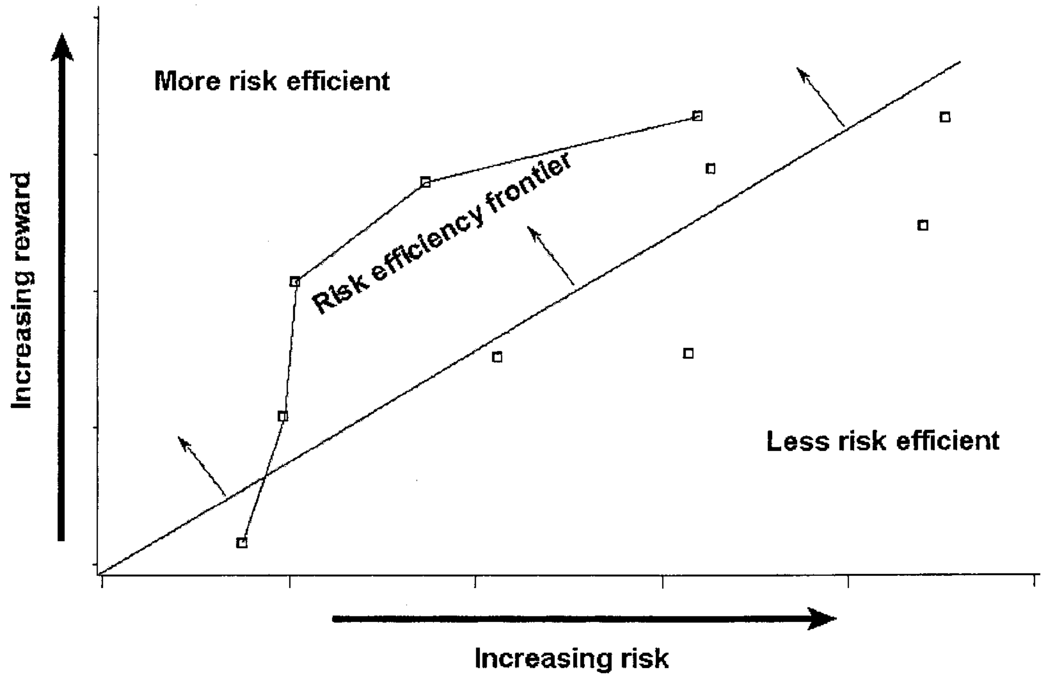


Figure 2. Theoretical consideration of risk efficiency. Low risk efficiency scenarios fall in the lower right quadrant, where increased risk does not result in higher reward. Scenarios with high risk efficiency fall into the upper left quadrant, where higher rewards are achieved with less risk. The risk efficiency frontier is comprised of scenarios that extract the highest reward with the lowest risk.

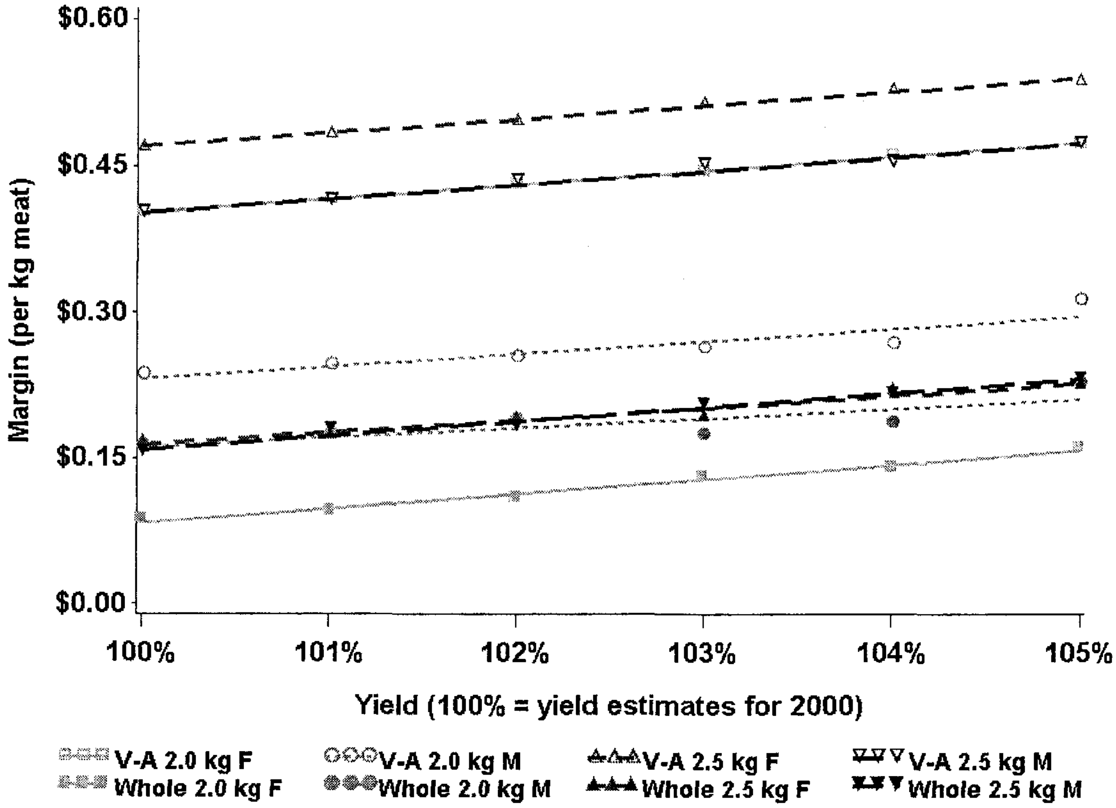


Figure 3. Sensitivity of supply chain margin to yield. Economic analysis of the profitability of light (2.0 kg) and heavy (2.5 kg) male and female broilers of the Ross x Ross 308 strain cross in value-added and whole bird market scenarios.

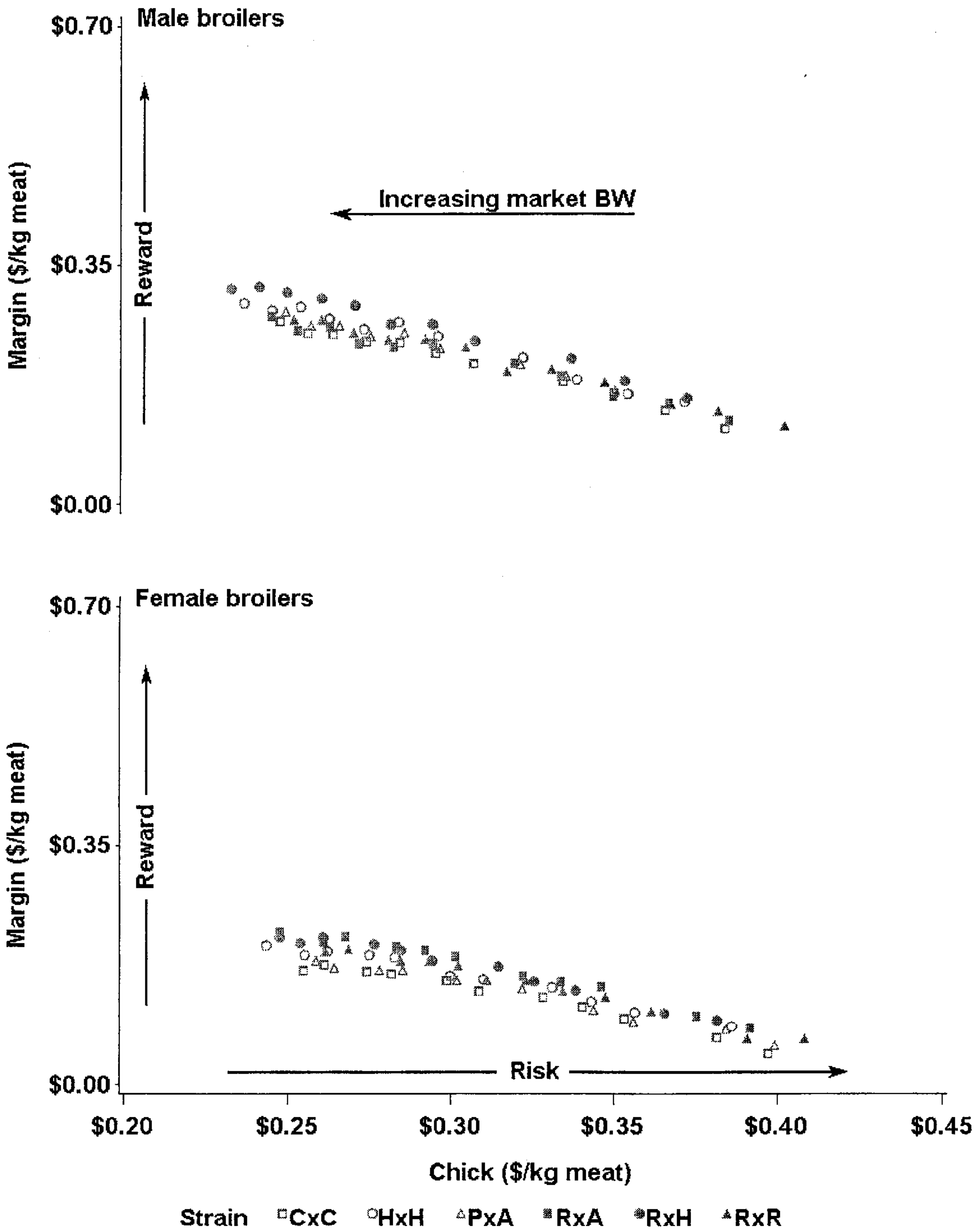


Figure 4. Tradeoff analysis for males and females of six commercial broiler strain crosses in a whole bird market scenario. Profitability is plotted as a function of the chick proportion of meat production costs.

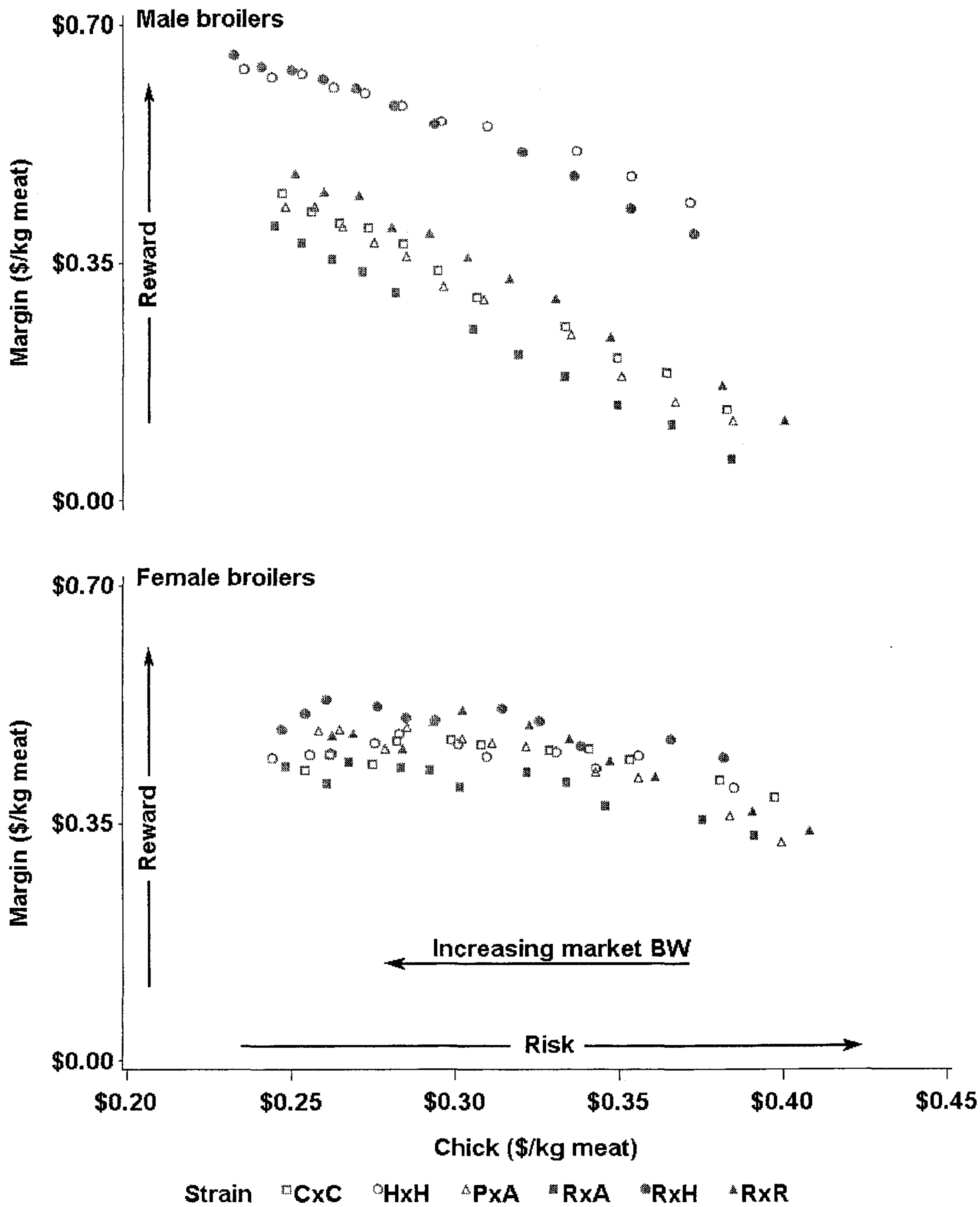


Figure 5. Tradeoff analysis for males and females of six commercial broiler strain crosses in a value-added market scenario where a premium is extracted for breast meat. Profitability is plotted as a function of the chick proportion of meat production costs.

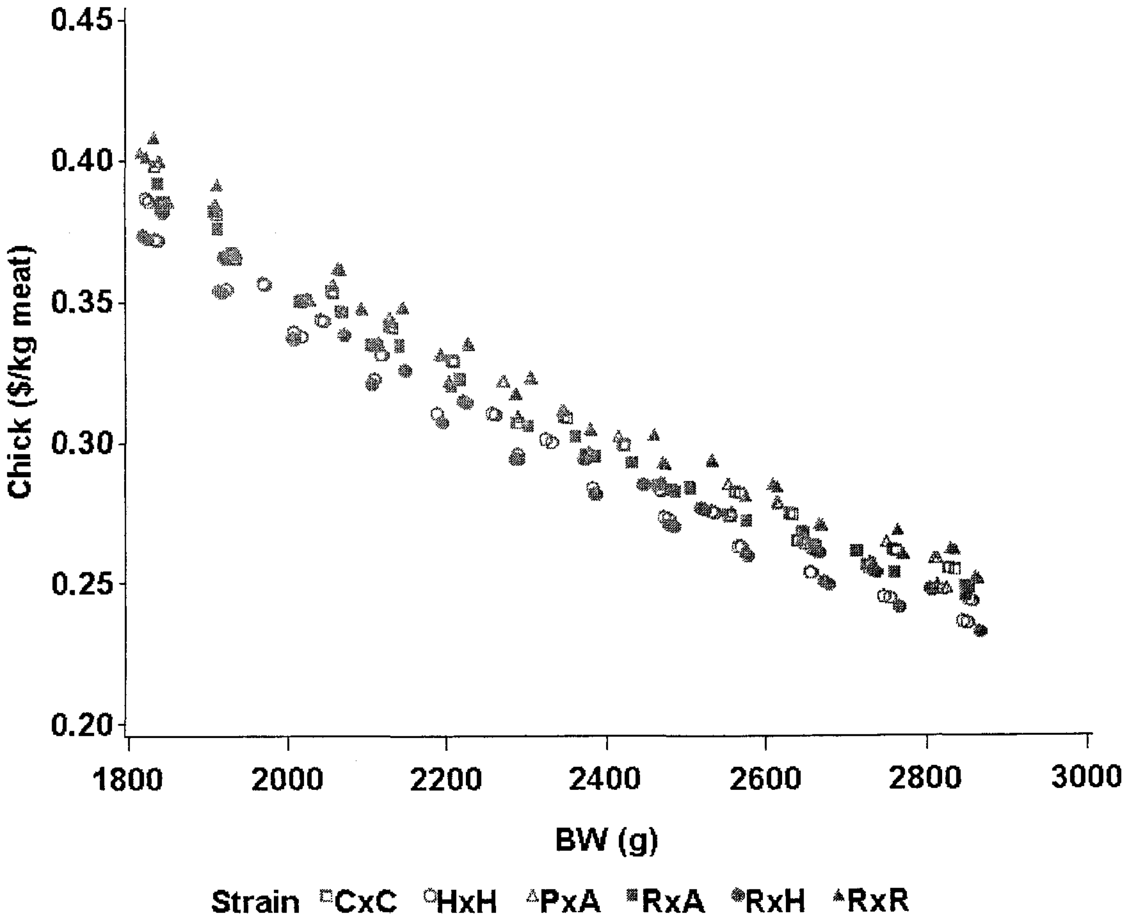


Figure 6. Relationship between market broiler BW and the chick cost fraction of meat production costs for males and females of six strains in two market scenarios.

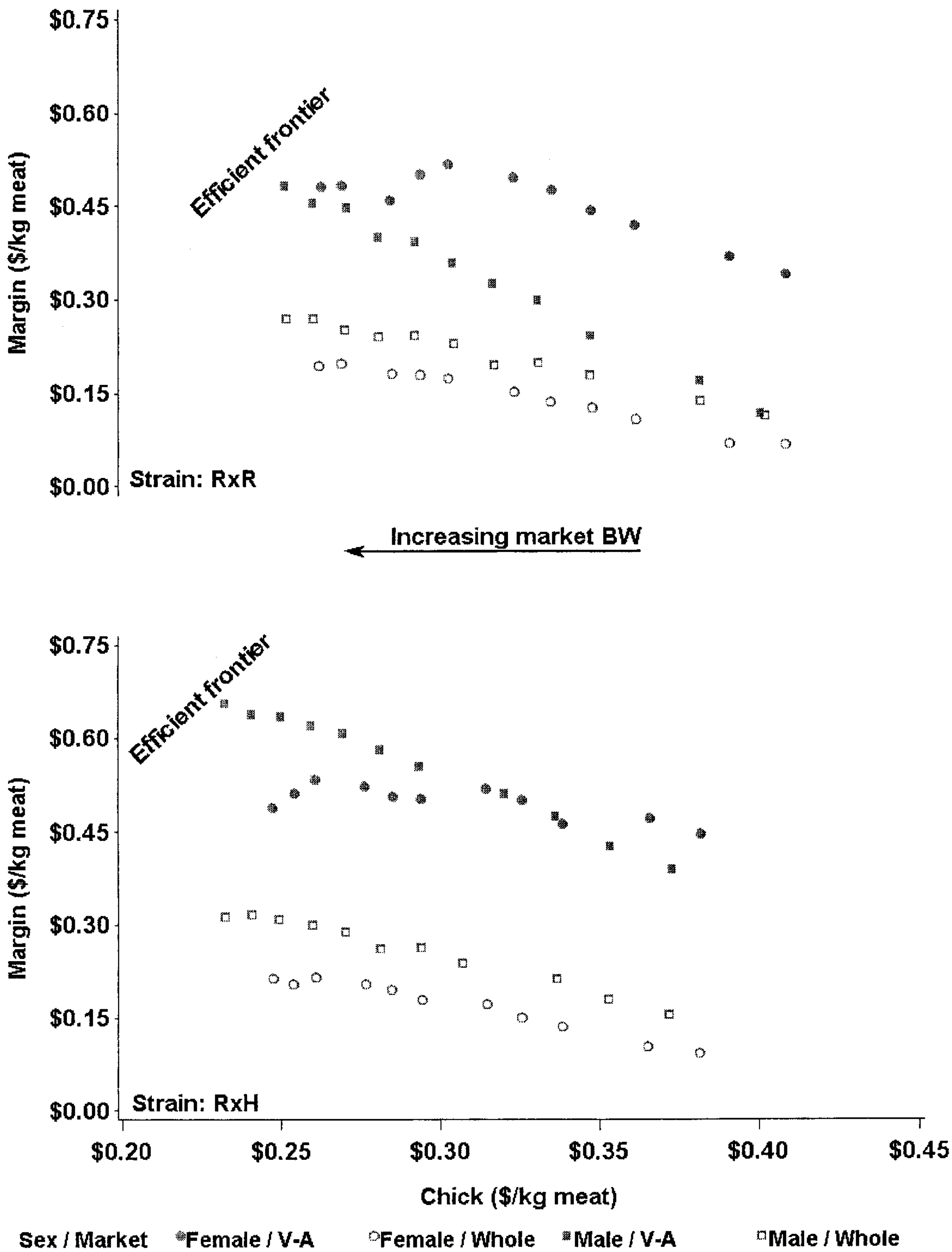


Figure 7. Tradeoff analysis plots for female and male broilers of the RxR and RxH strain crosses.

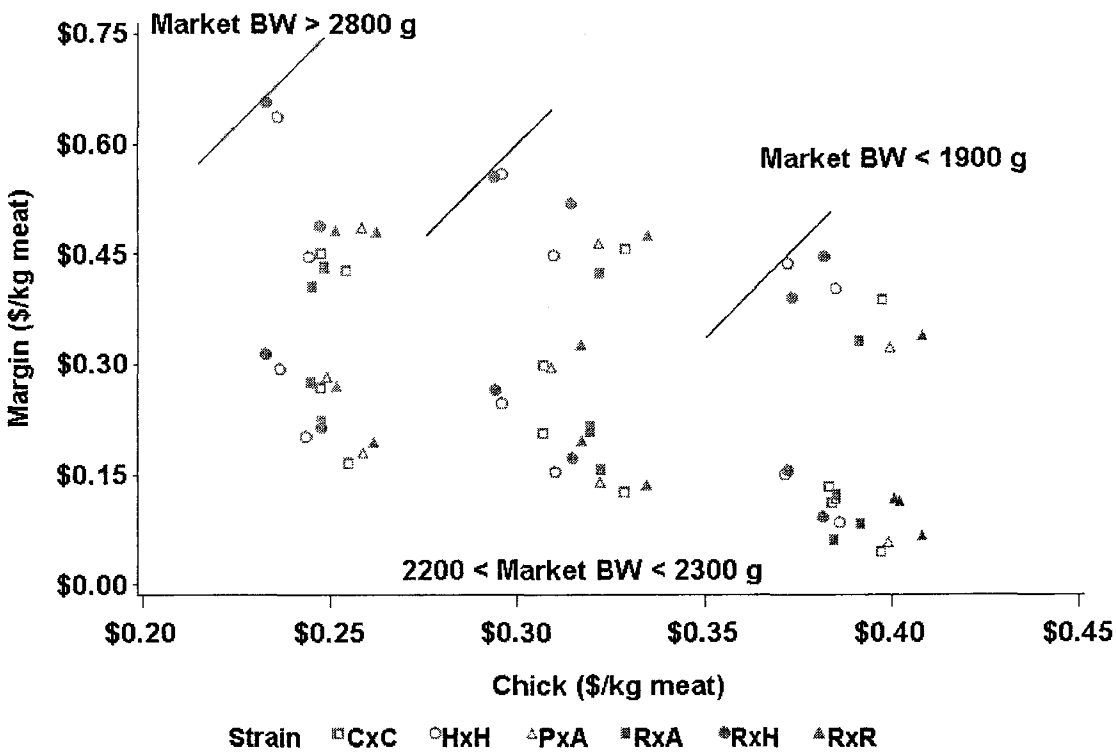


Figure 8. Risk efficiency frontier plots for males and females of six commercial strain crosses at three BW classes. Lines represent risk efficient frontier.

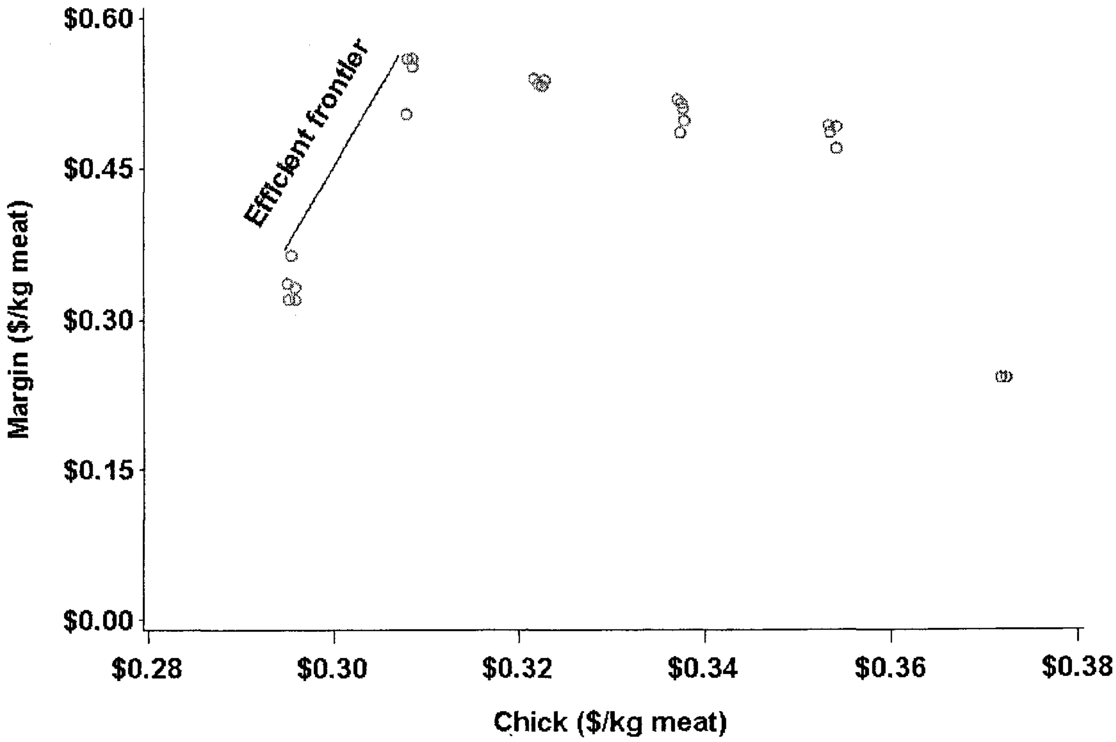


Figure 9. Risk efficiency frontier for HxR males in a value-added market scenario with product size constraints.

*References*

Carte, I. F. 1986. Genetic-economics of chicken meat production. Proc. of the 3rd World Congress on Genetics Applied to Livestock Production, Lincoln, Nebraska. Institute of Agriculture and Natural Resources

Federal Reserve Bank of Minneapolis. 2004. Federal Reserve Bank of Minneapolis - Consumer price index calculator. http://woodrow.mpls.frb.fed.us/research/data/us/calc/; accessed September, 2004.

Levins, R. 1966. The strategy of model building in population biology. Amer. Scientist 54:421-431.

Markowitz, H. 1952. Portfolio selection. The Journal of Finance 7:77-91.

McCown, R. L. 2001. Learning to bridge the gap between science-based decision support and the practice of farming: Evolution in paradigms of model-based research and intervention from design to dialogue. Austral. J. Agric. Res. 52:549-571.

Perillat, B. J., W. J. Brown, and R. D. H. Cohen . 2004. A risk efficiency analysis of backgrounding and finishing steers on pasture in Saskatchewan, Canada. Agric. Syst. 80:213-233.

Shapiro, J. F. 2001. Modeling the Supply Chain. Duxbury (an imprint of the Wadsworth Group, a division of Thomson Learning, Inc.), Pacific Grove, California, USA.

Sherwood, D. H. 1959. Restricting feed intake of meat-type breeder chickens. Poultry Sci. 38:1246.

Stoorvogel, J. J., J. M. Antle, C. C. Crissman, and W. Bowen. 2004. The tradeoff analysis model: integrated bio-physical and economic modeling of agricultural production systems. Agric. Syst. 80:43-66.

Zoons, J., E. Decuypere, and J. Buyse. 1992. Model based analysis of the profitability of sex separated broiler production. Landbouwtijschrift-Revue De L Agric. 45:519-530.

Zuidhof, M. J. 2004. A bioeconomic model of the broiler chicken supply chain. Chapter 6. A bioeconomic broiler processing model. Ph.D. Thesis. University of Alberta.

Appendix 1. Base broiler economic scenario for supply chain margin analysis.

## Broiler Chicken Economic Model

**Comments**

**Strains** Ross x Ross 308

**Benchmarks**

| | | | |
|---|---|---|---|
| Placement date: 5/31/2004 | | Marketing date: 7/ 9/2004 | |
| Quota units (farm size) | 50,000 | Utilization factor (% of quota) | 99.800% |
| Quota leased in(out) (kg) | 0 | Conversion factor (kg/quota unit/wk) | 0.3700 |
| Chicks placed per cycle | 74,787 | Cycle length (wk) | 8 |
| Chicks paid for ( 2.0% free) | 73,320 | Cycles per year | 6.522 |
| Birds marketed per cycle | 73,852 | Bird age at marketing (days) | 39 |
| Live production per cycle (kg) | 147,704 | Mortality (%) | 0.0000% |
| Market weight (kg) | 2.0000 | Condemns(%) | 1.2500% |
| Live broiler price ($/kg) | 1.1980 | Chick weight (g) | 42.00 |
| Premium ($/kg) | 0.0000 | **Stocking Density** | |
| Barn space (sq ft) | 50,000 | sq ft/bird placed | 0.6686 |
| Barn cost ($/sq ft) | 11.0000 | sq ft/bird marketed | 0.6770 |
| Equipment cost ($/sq ft) | 4.3500 | kg marketed/sq ft | 2.9541 |

**Capital Costs**

| | |
|---|---|
| Land $1,000/acre | 20,000 |
| Building | 550,000 |
| Equipment | 217,500 |
| Shop | 10,000 |
| Mobile equipment | 10,000 |
| Quota $41.72/unit | 2,086,000 |
| Total Capital Costs | 2,893,500 |

**Feed Costs**

| | | Consumption (kg/bird) | $/tonne | $/bird |
|---|---|---|---|---|
| Feed conversion rate | 1.8000 | | | |
| Starter | | 0.200 | 318.00 | 0.0636 |
| Grower | | 0.400 | 281.00 | 0.1124 |
| Finisher | | 1.524 | 273.00 | 0.4162 |
| Finisher II | | 1.400 | 252.50 | 0.3535 |
| Other | | 0.000 | 252.50 | 0.0000 |
| Weighted feed cost | | | 268.32 | 0.9457 |

**Fixed Costs**

| | Annual | $/cycle | $/kg |
|---|---|---|---|
| Money borrowed: $ 80,000 ( 2.76% of investment) | | | |
| **Loan payment** | 83,176 | 12,753 | 0.0863 |
| Principal portion | 77,376 | 11,863 | 0.0803 |
| Interest portion (@7.250%) | 5,800 | 889 | 0.0060 |
| Debt servicing ratio 3.542 | | | |
| Insurance | 5,800 | 889 | 0.0060 |
| Taxes | 6,150 | 943 | 0.0064 |
| **Depreciation** | 102,500 | 15,715 | 0.1064 |
| Building (10%/yr) | 56,000 | 8,586 | 0.0581 |
| Equipment (20%/yr) | 43,500 | 6,669 | 0.0452 |
| Mobile Equipment (30%/yr) | 3,000 | 460 | 0.0031 |
| Quota ( 0.00%/yr) | 0 | 0 | 0.0000 |
| Total Fixed Costs | 120,250 | 18,437 | 0.1248 |

Printed: 7/28/2004 File: ECONOMIC SCENARIOS.CO2 BCSCM version 2.46 page 1 of 2

| Variable Costs | $/unit | $/cycle | $/kg |
|---|---|---|---|
| Chick | 0.5550 | 40,693 | 0.2755 |
| Vaccination | 0.0000 | 0 | 0.0000 |
| Sexing | 0.0000 | 0 | 0.0000 |
| Feed | 268.32 | 70,723 | 0.4788 |
| Catching (per bird caught) | 0.0601 | 4,495 | 0.0304 |
| Utilities / Energy ($ / month) | 2,300 | 4,293 | 0.0291 |
| Labour (8.69 hours/flock/day) | 12.00 | 5,840 | 0.0395 |
| Repairs (0.8635% of capital costs) | 6,800 | 1,043 | 0.0071 |
| Veterinary | | 350 | 0.0024 |
| Litter | | 375 | 0.0025 |
| ACP levy | 0.0125 | 1,846 | 0.0125 |
| Quota leased in (out) 0 kg @ 0.0000 /kg | | 0 | 0.0000 |
| Market development quota 0 kg @ 0.0000 /kg | | 0 | 0.0000 |
| Miscellaneous | | 290 | 0.0020 |
| Total Variable Costs | | 129,947 | 0.8798 |

| Summary of Costs and Returns | annual | $/cycle | $/kg |
|---|---|---|---|
| **Summary of income** | | | |
| Base income (live production) | 1,154,121 | 176,949 | 1.1980 |
| Premium | 0 | 0 | 0.0000 |
| Miscellaneous | 0 | 0 | 0.0000 |
| Total income | 1,154,121 | 176,949 | 1.1980 |
| **Summary of expenses** | | | |
| Feed and chick cost | 726,690 | 111,416 | 0.7543 |
| Other variable costs | 120,869 | 18,532 | 0.1255 |
| Total fixed costs | 120,250 | 18,437 | 0.1248 |
| Total expenses | 967,809 | 148,384 | 1.0046 |
| **Margins** | | | |
| Over feed and chick | 427,431 | 65,534 | 0.4437 |
| Over total variable costs | 306,562 | 47,002 | 0.3182 |
| Over all costs (net return) | 186,312 | 28,565 | 0.1934 |
| Cash flow (before loan principal payment) | 288,812 | 44,281 | 0.2998 |
| Cash flow (after loan principal payment) | 211,436 | 32,417 | 0.2195 |
| Break even for all cash outlays | 942,685 | 144,532 | 0.9785 |
| Break even income | | | 1.0046 |
| Gross income | | | 1.1980 |
| **Net Return** | | | |
| (per bird shipped) | | $0.3868 | |
| (per kg shipped) | | | $0.1934 |
| (per kg shipped and paid for) | | | $0.1934 |
| (per square foot) | | | $0.5713 |

Printed: 7/28/2004 File: ECONOMIC SCENARIOS.CO2 BCSCM version 2.46 page 2 of 2