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Simulating economic values of a genetic improvement program for Australian farmed saltwater crocodiles*

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In genetic improvement programs, candidates for breeders are ranked by the profitability of their offspring, expressed as a weighted sum of the genetic gain from selection. In this paper, we estimate the economic values of a genetic improvement program for Australian farmed saltwater crocodiles. A bioeconomic profit function for a representative breeding pair is used to determine the optimal slaughter age following genetic improvement in each selection objective. The results indicate that estimated farm profitability increases by nearly \$A111 for a 1-week reduction in juvenile slaughter age, \$A78 for a 1 per cent increase in the proportion of first-grade skins produced, and \$A33 for an increase in the number of viable hatchlings per clutch. The implications of the analysis for the Australian crocodile industry and the limitations of the research are explored.

Key words: bioeconomic model, crocodiles, economic values, genetic improvement.

1. Introduction

Until recently, research in the Australian crocodile industry has focused on husbandry practices, to the exclusion of genetics. The research by Isberg *et al.* (2004), commissioned by the Rural Industries Research and Development Corporation (RIRDC), and undertaken in collaboration with the University of Sydney and Janamba Croc Farm, contained recommendations for the first practical genetic improvement program for use in the industry. Isberg *et al.* (2003) suggested possible selection objectives (genetic traits under selection) for implementing a genetic improvement program, which were classified into three groups: reproductive performance (e.g., number of hatchlings per clutch, nesting frequency), production (e.g., survival, age at slaughter), and quality (e.g., skin grade). These were included in a questionnaire sent to members of the Australian crocodile industry, including farm managers, government

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officials and researchers, reported in Isberg *et al.* (2004). The survey was designed to quantify the level of support for a genetic improvement program and identify the priorities for increasing production efficiency on Australian farms. Based on the responses received, the selection objectives were defined as follows: to increase breeder output by one viable hatchling per clutch, to increase juvenile survival by 1 per cent, to reduce slaughter age by 1 week, and to decrease weekly feed consumed by 1 g per juvenile.

This paper is an extension on the final stage in the development of the genetic improvement program for farmed saltwater crocodiles. We simulate the economic values required to weight each selection objective. We measure the increase in farm profit arising from the production of genetically improved crocodiles, through the selection of breeders that are superior in the relevant traits. The change is quantified within a framework of profit maximisation, expressing genetic improvement as a shift or change in the slopes of biological functions simulating crocodile growth.

In Section 2, the key features of the Australian crocodile industry are outlined to demonstrate the competitive pressures faced by producers. Section 3 provides a background to genetic improvement programs and the methods used to simulate economic values. In Section 4, the bioeconomic model is presented. In Section 5, the economic values for the base case and alternate scenarios are described, and they are discussed in Section 6.

2. Background

The Australian crocodile industry is heavily dependent on the production of saltwater crocodiles for their skins, which are manufactured into luxury leather goods. Crocodiles are harvested when they have a belly width between 35 and 45 cm, as this is the industry-preferred range for the handbag market, to minimise wastage during product manufacture. There is occasional demand for smaller skins to be manufactured into small leather goods such as watchstraps, and for larger skins (greater than 50 cm) in response to fashion trends toward larger-sized handbags (MacNamara *et al.* 2003). Skins are sold on a $US/cm belly width basis in conjunction with a stringent, yet subjective, grading system dependent on the presence and number of blemishes on the belly area. A first-grade skin has no blemishes, four appendages, and appears well preserved. The presence of any bite marks, abrasions, or knife holes results in an automatic downgrading of the skin (Manolis *et al.* 2000), and although prices increase with belly width, only first-grade skins command a premium export price. Table 1 presents a range of prices indicative of those received by Australian producers.

Trade in crocodilian[1] skins can be divided into 'classic' skins versus others, such as caiman and alligator. Saltwater crocodile skins are considered aesthetically

[1] The term 'crocodilian' includes species in addition to saltwater crocodiles, such as alligators and caimans. We use this term when referring to the wider industry of which Australian crocodile producers are a part.

Table 1 A range of prices received by Australian producers for saltwater crocodile skins (salted)

	Prices received per centimetre ($US/cm)		
Belly width (cm)	First-grade	Second-grade	Third-grade
25–34	6.00		
35–39	8.00	3.20–3.85	1.28–1.93
40–45	9.00		
46–50	10.00–11.00		

Source: S. Barker pers. comm., 2003.

Table 2 Market shares and prices for crocodilian skins

		Prices ($US/cm) for salted skins ≥ 36 cm width	
Species	Market share (%)	First-grade skins	Second-grade skins
Alligator	20.6	4.50–5.00	N/A
Nile crocodile	8.7	3.70	2.50–3.00
Saltwater crocodile	1.9	9.00–9.50	3.50–4.00

Source: MacNamara *et al*. (2003).

superior due to a higher number of scale rows of a smaller, more evenly distributed pattern compared with that of other crocodilians (MacNamara *et al.* 2003). Another advantage is the absence of skin bones in the belly scales, which increase the risk of tearing during tanning and produce a pitted, discoloured appearance in the finished skins (Thorbjarnarson 1999). Nevertheless, the strictness of the skin grading system has significant revenue repercussions for producers. Buyers prefer a constant supply of first-grade, blemish-free skins of lower ‘quality’ (such as American alligator) to a blemished saltwater crocodile skin. As seen in Table 2, a first-grade alligator skin receives a significantly higher price than that received for a similarly wide, second-grade saltwater crocodile skin.

The market for crocodilian skins is characterised by price fluctuations, with recent downturns in 1992 and 1996. These were caused, in part, by the relatively inelastic supply of crocodilian products, as the length of the production period limits the ability of the industry to adjust to price changes (Woodward *et al.* 1993). More important are the shifts in the elastic demand for crocodilian products. Although there is little evidence that either changing sentiments in the fashion industry or consumer resistance to animal products are behind the shifts, the general economic status of consuming countries is held to be a principal determinant of demand (Hutton *et al.* 2001). As luxury goods, products manufactured from crocodile leather are highly income-elastic, implying that demand is reliant on economic prosperity and higher incomes. In times of recession, consumers are likely to defer or discontinue purchases of exotic leather, or substitute away from 'classic' crocodilian products toward relatively less expensive products such as caiman, ostrich, or snake skin. The 1996 downturn was seemingly attributed to the Asian economic crisis, as Asia is the principal end-market for luxury crocodilian products. However, Australian producers were less severely affected than producers of lower quality skins. This development seemingly emerged as a result of the skins of saltwater crocodiles having traditionally been in short supply (limiting stock accumulation by traders, tanners, and manufacturers prior to the price fall in 1992), and because of the higher quality of saltwater crocodile skins (Hutton *et al*. 2001).

Australia exports skins to France, Italy, Japan, and Singapore (MacNamara *et al*. 2003). The French market for first-grade skins is highly dependent on fashion house Hermes' demand, although there are no indications that the historically stable demand will falter in the future. In addition, the three major tanneries for exotic skins can sell more skins than Australian producers supply. Particularly, there have also been indications that tanneries would promote first-grade skins to other fashion houses such as Prada. In Italy and Japan, even first-grade skins face stiff competition and declining prices. This is driven by strong preferences for alligator leather in the USA, the major market for finished products from Italy, and competition from other crocodilian skins and alternative exotic species (MacNamara *et al*. 2003).

The largest concern of skin buyers is the shortage of first-grade skins, as many fail to meet the grading requirements (Manolis *et al*. 2000). MacNamara *et al*. (2003) suggested that 50 per cent of crocodile skins currently produced met first-grade requirements, whereas Isberg *et al*. (2003) estimated a figure of nearly 30 per cent first grade. The pricing regime, as demonstrated in Tables 1 and 2, makes it apparent that farm revenue is dependent on producing a high proportion of first-grade skins.

Developing an economic selection index to select future breeders allows the producer to address traits that affect farm revenue (Goddard 1998). This would enable producers to take advantage of the strong demand for first-grade skins. Given the large proportion of skins that are second- or third-grade, genetic traits that influence the costs of production should also be included as selection objectives in the economic selection index.

3. Theoretical considerations

A genetic improvement program is founded upon the selection of future breeders for more than one trait (e.g., growth rate and fertility) to improve the economic value of the herd (Smith 1983). Selection of candidates is based on an economic selection index, where the overall profitability of a potential breeder is the weighted sum of the estimated breeding value for each selection objective, and the weights are the economic values (Bourdon 2000).

$$H = v_1EBV_1 + v_2EBV_2 + \ldots + v_mEBV_m \quad (1)$$

where H is the aggregate breeding value for profitability, v_i is the economic value for the ith selection objective in the breeding program, EBV_i is the estimated breeding value for the ith selection objective in the breeding program, and m is the total number of selection objectives in the breeding program.

The economic values indicate the relative importance of a marginal change in the trait as a dollar value. When combined into the economic selection index of an individual, they weight the EBV for each selection objective. This yields the best estimate of the aggregate (true) breeding value of each candidate available for selection, in a single dollar value, which producers can use as a decision tool in selecting future breeders.

Although breeders may make genetic selection decisions based on profit-maximising objectives, they cannot merely enhance desirable characteristics. Analysing genetic improvement in terms of production theory fails to take into account the heterogeneity of animal inputs, and there is no market for the specific genetic traits under selection. The characteristics are subsumed under a single purchasable input, the breeding animal, purchased in the expectation that desirable characteristics will be inherited by their offspring (Kerr 1984). Another approach based on the induced innovation hypothesis postulates that the emergence of new technology is driven by market forces (Sunding and Zilberman 2001). Technical change substitutes abundant factors of production for scarce factors, where scarcity is captured by relative prices. Hence, changes in the relative factor prices result in biased technical change. Yet, as Kerr (1984) notes, the potential for genetic improvement remains for livestock regardless of whether or not there have been changes in relative factor prices. Moreover, genetic improvement may be driven by demand pressures, reflecting quality concerns in the marketing chain (Walburger 2002).

If the value of the breeding animal in production is related to its inherent genetic worth, then improvements should also be reflected in the breeding animal's value (Walburger 2002). By considering derived demand for an input into production as a function of its characteristics, hedonic modelling can be used to measure the implicit values of genetic characteristics for which there is no market. In modelling technical change in the Canadian beef cattle industry, Kerr (1984) identifies genetic improvement as a shift in the production function and quantifiable additions to existing characteristics. He defines the production function as:

$$Y_B = F^B(g, x) \tag{2}$$

where Y_B is output/bull/year, g is the bull component of the production function and a vector of genetic characteristics, and x is a vector of non-genetic inputs. Kerr (1984) suggests that a profit-maximising firm uses non-genetic inputs up until the price of each input equals its marginal value product, $W_j = P_Y(\partial Y_B / \partial X_j)$. He then notes that the value of the bull will be determined by what it adds to production, so that:

$$W_g = P_Y Y_B - \sum_{j=1}^{m} W_j X_j^* \tag{3}$$

where W_g is the value of the bull, P_Y is output price, W_j is the price of input j, X_j^* is the optimum quantity of input j, and m is the number of non-genetic inputs.

Following some simple manipulations and using Euler's theorem, W_g becomes:

$$W_g = \sum_{i=1}^{m} G_i \frac{\partial Y_B}{\partial G_i} P_Y . \tag{4}$$

If purchasers of bull semen can recognise important genetic inputs, then this should be reflected in the prices they are willing to pay for the semen of a particular bull. Moreover, as a bull contributes to production over its breeding life, its value should be calculated for its productive life, giving:

$$P_B = \sum_{i=1}^{m} G_i \frac{\partial Y_B}{\partial G_i} \sum_{i=1}^{t} P_{yt} . \tag{5}$$

where P_{yt*} is the discounted expected value of P_y in time t. Accordingly, if Equation (5) can be estimated, then the economic values of traits G_i can be derived as $\partial P_B/\partial G_i$ (Kerr 1984).

The Kerr (1984) hedonic method poses some difficulties for saltwater crocodiles. There is no market for breeders, as breeding stock are mainly derived from wild-caught animals (Isberg *et al*. 2004). As such, it is not possible to use a hedonic model to find implicit values of attributes based on the prices producers are willing to pay for breeders. Prices received for skins are subjectively determined and do not capture the juvenile attributes related to productive efficiency. Although a hedonic method could potentially value skin quality, grading currently reflects physical damage, and premium prices are not offered for superior patterned skins within a grade.

Alternative methods based on production economics involve calculating economic values using a non-linear production function. Amer *et al*. (1994) employ a generalised Cobb–Douglas function (Equation 6), representing genetic improvement in traits A and x_1, as in Equations (6) and (7):

$$y = A x_1^{\alpha} x_2^{\beta} \tag{6}$$

$$y = A(1 + \lambda_A)\left(\frac{x_1}{1 - \lambda_1}\right)^{\alpha} x_2^{\beta} \tag{7}$$

In this way, both neutral improvements $\{A \rightarrow A(1 + \lambda_A)\}$ that leave the optimal input ratio unchanged, and non-neutral improvements $\{x_1 \rightarrow x_1/(1 - \lambda_1)\}$ that change the relationship between the level of input use and farm output, were represented (Amer *et al*. 1994). As Amer *et al*. (1994) are principally concerned with showing that genetic improvement that alters the optimal input ratio results in a greater change in profit than when economic values are calculated as the derivatives of a linear profit function, the choice of the Cobb–Douglas functional form appears appropriate. But this is more an indication of the function's usefulness than its suitability for representing genetic improvement. For example, Amer *et al*. (1994) discuss genetic improvement as a heavier final carcase weight (A in Equations 6 and 7), although there is no indication of how this is achieved, such as through faster growth rates and a constant production period, or greater feed-conversion efficiency. It is worth noting that in Amer *et al*. (1997), underlying biological functions are included to emphasise the importance of a genotype-specific slaughter point for UK beef cattle. They optimise slaughter time before and after genetic improvement by equating marginal carcase revenue at time t to the marginal cost of keeping the animal in the system for a further unit of time, using a biological growth model to calculate carcase quality characteristics over time.

To simulate the economic values for farmed saltwater crocodiles, we followed the method of Amer *et al*. (1997), maximising profit for a representative breeding pair. Only neutral improvements were allowed and, of the management controlled variables, only slaughter age was varied. Profit is maximised following an improvement in a selection objective, resulting in a new optimal slaughter age for juveniles.

4. Empirical model, data, and procedures

Economic values were simulated for a representative breeding pair using a profit function for Australian farmed saltwater crocodiles, developed in the form of a bioeconomic model for determining optimal slaughter age. Confidential data were provided by Janamba Croc Farm in the Northern Territory. Only animals that have been together for several years, have produced multiple clutches, and are maintained in breeding pens, were included in the study, to allow individual dams and sires to be distinguished. Juveniles are identified for their clutch and hatching year through scute cutting, which involves the removal of a unique sequence of the raised, triangular osteoderms along the animal's dorsal surface (Isberg *et al*. 2004).

The biological functions and parameters of the model were specified to simulate a representative breeding pair of Janamba Croc Farm. Parameter values are not presented here as they are commercial in confidence, but they can be obtained from the authors. Juvenile survival in Equation (8) gives the proportion of juveniles surviving up until at least time t:

$$S(t) = \exp^{[-(t/\kappa)^{\rho}]} \tag{8}$$

The distribution for survival times is based on a hazard function, describing the instantaneous risk of failure (death) at time t, given that the individual is alive immediately prior to t (McCullagh and Nelder 1989). The underlying Weibull hazard function has the property $0 < \rho < 1$ to describe a decreasing hazard with time, as mortality rates fall as juveniles mature. Isberg *et al*. (2004) suggest that survey results indicate survival is rated most important by producers, with few farmers reaching the survival rates recommended as achievable of 95 per cent in the first year and 95 per cent between 1 year old and slaughter (Webb 1989). Although survival rates are affected by management regimes, Isberg *et al.* (2004) noted that genetic effects might also have an impact. A benefit arising from simulating a survival function is that it is an alternative to estimating that non-surviving juveniles incur some percentage of operating costs.

Juveniles can take between 2 and 5 years to reach harvest size for the handbag market, averaging about 3.5 years, and improvements in growth rates were rated highly by survey participants. Average juvenile belly width is described by a logistic function in Equation (9) that follows Engel and Bassanezi (1997). This yields belly width as a constant proportion (w) of total length:

$$W(t) = w \cdot \left[\frac{1}{a + b\exp^{-ct}} \right] \tag{9}$$

Revenue earned per skin depends on the price received per centimetre belly width, $P_{i,t}$. Within a certain skin-width range and price bracket, average price is a weighted average, depending on the proportion of skins in each grade, θ_i ($i = 1$–3), given in Equation (10):

$$\begin{aligned} &\theta_1(t) = \{1 + \exp[-(\alpha_1 - \beta t)]\}^{-1}, \\ &\theta_2(t) = \{1 + \exp[-(\alpha_2 - \beta t)]\}^{-1} - \{1 + \exp[-(\alpha_1 - \beta t)]\}^{-1}, \qquad \text{and} \\ &\theta_3(t) = 1 - \{1 + \exp[-(\alpha_2 - \beta t)]\}^{-1}. \end{aligned} \tag{10}$$

The proportion of skins that are first-grade declines with age, t. This stems largely from physical damage to skins due to inappropriate management regimes, particularly with regard to stocking densities. Although fighting can be reduced by minimising the size disparity between juveniles in a pen, Isberg *et al.* (2004) present anecdotal evidence that some clutches are more aggressive, implying a possible basis for genetic improvement of skin grade. We assumed that 45 per cent of skins were first-grade pre-improvement.

The juveniles are fed *ad libitum*, initially a minced meat mixture of red meat and chicken heads and eventually chicken heads alone. Treadwell *et al.* (1991) suggested that a crocodile harvested at 1.5 m length would have consumed on average 120 kg of food, making feed the largest component of the operating costs of crocodile farms, at 42–45 per cent (Treadwell *et al.* 1991). Hatchlings are fed five times a week, gradually reduced to twice a week in cooler months and three times a week in warmer months during the grow-out phase. In the cost component of the model, the average amount of feed consumed per week depends on instantaneous feed consumed $f(t)$ (Equation 11) and the survival function $S(t)$. This gives the cumulative amount of feed consumed up to time t, $\bar{F}(t)$ in Equation (12). Feed price P_F was assumed constant:

$$f(t) = x - z\exp^{-ut} \tag{11}$$

$$\bar{F}(t) = \int_0^t f(t)S(t)\,dt \tag{12}$$

Operating costs including labour, $D(t)$, which is around 40 per cent of operating costs (Treadwell *et al.* 1991), were assumed constant per unit of time and dependent on the number of juveniles in the system. Capital costs, K, were assumed constant over t and dependent on A, the number of hatchlings per clutch, and feed costs per breeding pair were excluded.

The profit function (Equation 13) is specified for the long-run, and the farm maximises profit when marginal economic profit equals zero, and all inputs are receiving a payment:

$$\pi = A\cdot\left[\sum_{i=1}^{3} P_{i,t}\cdot\theta_i(t)\right]\cdot S(t)\cdot W(t) - A[P_F\cdot\bar{F}(t) + D(t)\cdot S(t) + K] \qquad (13)$$

Prior to genetic improvement, profit is maximised with respect to slaughter age t (in weeks), as in Equation (14). Other management-controlled variables were not optimised, because the quantities of the physical inputs used are dependent on what is needed to sustain a predetermined genetic level of performance (Tess *et al.* 1983), and the number of juveniles in the production system.

$$\frac{d\pi}{dt} = A\left\{\begin{aligned}&\left[\sum_{i=1}^{3} P_{i,t}\theta_i'(t)\right]\cdot S(t)\cdot W(t) + \left[\sum_{i=1}^{3} P_{i,t}\theta_i(t)\right]\cdot S'(t)\cdot W(t)\\ &+\left[\sum_{i=1}^{3} P_{i,t}\theta_i(t)\right]\cdot S(t)\cdot W'(t)\end{aligned}\right\} \qquad (14)$$

$$- A[P_F\cdot S(t)\cdot f(t) + D\cdot S'(t)] = 0$$

Genetic improvement in the selection objectives is affected through the alteration of parameters in the biological functions given in Equations (8) to (12). An improvement in the number of hatchlings per clutch (NoHatch) by one viable hatchling is represented as a shift in $A \rightarrow (A + \lambda_A)$. An improvement in juvenile survival (Surv) is represented by new values for ρ and κ in Equation (8) to give a 1 per cent increase in juvenile survival at time of slaughter. An increase in the proportion of skins that are first-grade (%First) is represented by a shift $\beta \rightarrow (\beta - \lambda_B)$ in Equation (10). This slows the rate at which the proportion of first-grade skins declines. A reduction in feed consumed per juvenile (FeedCons) by 1 g per week is represented by $x \rightarrow (x + \lambda_x)$ in Equation (11). This shifts the instantaneous feed consumed function down by 1 g for all values of t. An improvement in the selection objective slaughter age (SlautAge) is represented by $c \rightarrow (c + \lambda_c)$ in Equation (9), which increases the slope of the function, and hence the growth rate of the juvenile crocodiles.

Economic values were calculated as the change in profit following genetic improvement and the re-optimisation of slaughter age. Sensitivity analyses were carried out on the parameters of the biological functions and the management and marketing systems to test their sensitivity. Percentage changes

Table 3 Base case economic values of trait improvements

Optimal slaughter age (weeks)	Profit per breeding pair ($A)	NoHatch	SlautAge	Surv	FeedCons	%First	Re-optimised slaughter age
141.57	1025.43	32.81	111.50	30.34	4.75	77.84	140.69
		Contribution of traits to the aggregate breeding value					
		0.13	0.43	0.12	0.02	0.30	

in price and production costs were chosen to reflect possible future conditions faced by managers of Australian farms, as well as different phenotypic characteristics for the juveniles to accommodate small differences in the specification of the biological functions. These included a higher proportion of first-grade skins, through adjusting β in Equation (10), and different growth rates and hatching lengths, through adjusting c and b, respectively, in Equation (9).

5. Results

The economic values per representative breeding pair for the base case are displayed in Table 3. Juveniles are optimally slaughtered as soon as they reach the industry-preferred belly width range of 35–45 cm. In all scenarios assessed, the optimal slaughter age coincided with a lower limit of the belly width range in a price bracket, as the increasing width of skins with t failed to compensate for the declining proportion of first-grade skins, and the accompanying decline in average price. In the base case, profit per breeding pair was approximately $A1000. In terms of relative importance as a weight in the economic selection index, SlautAge contributed most to the aggregate breeding value (43 per cent), corroborating the high importance assigned to growth rates by survey participants. The economic value of $A111 represents the cost savings from reducing the production period by one week, and the gains in revenue from selling skins for a higher average price, due to the marginally higher proportion of first-grade skins at the earlier age. %First was second in relative importance (contributing 30 per cent of aggregate breeding value) with an economic value of $A78 for an improvement in the proportion of first-grade skins by 1 per cent. The economic value of $A33 for NoHatch reflects the profit from increasing the number of viable hatchlings by one per clutch. The economic value of $A30 for Surv includes the benefits of reduced mortality costs, which are the operating costs incurred by non-surviving juveniles, and as such the costs of raising an animal for no economic return, and the profit from a greater number of skins sold per clutch. The economic value for FeedCons of $A5 is small due to the magnitude of the improvement considered, namely a reduction of 1 g per week. However, as Webb (1989) observes that crocodiles have high feed conversion efficiency, this implies that further improvement might not be as valuable as improvements in other traits that are relatively less efficient.

Table 4 Economic values and contributions to aggregate breeding value (figures in brackets) of traits under conditions that affect price received by producers

Exchange rate	Profit per breeding pair ($A)	Economic values					Re-optimised slaughter age
		NoHatch	SlautAge	Surv	FeedCons	%First	
–5%	1405.23	44.97 (0.16)	114.61 (0.41)	34.29 (0.12)	4.75 (0.02)	81.94 (0.29)	140.69
+5%	681.79	21.82 (0.09)	108.69 (0.46)	26.77 (0.11)	4.75 (0.02)	74.17 (0.31)	140.69
+10%	369.40	11.82 (0.05)	106.13 (0.49)	23.52 (0.11)	4.75 (0.02)	70.77 (0.33)	140.69
Price							
–5%	664.61	21.27 (0.09)	108.55 (0.46)	26.59 (0.11)	4.75 (0.02)	73.95 (0.31)	140.69
+5%	1386.24	44.36 (0.16)	114.45 (0.41)	34.09 (0.12)	4.75 (0.02)	81.74 (0.29)	140.69

Harris and Freeman (1993) argue that economic values derived for current prices and costs are valid only if production and market conditions are expected to be stable into the future. However, Smith (1983) concludes that frequent revision of economic values to accommodate small changes arising from new husbandry techniques and changes in market conditions or increased productivity of improved livestock is unnecessary, as the effect on the efficiency of the selection index will be small. This view is arguably better for Australian saltwater crocodiles, due to the time required for genetic improvements to be expressed. To confirm this, sensitivity analyses were conducted on price received, production costs and productive attributes. Although profit per breeding pair and the magnitudes of the economic values were sensitive to these changes, their relative importance was largely unaltered for the less extreme of the changes considered. Scenarios that affect price received by producers are displayed in Table 4. NoHatch had the largest change in relative importance, falling to 5 per cent following a 10 per cent appreciation of the exchange rate. This was sufficient to increase the relative importance of SlautAge and %First, even though their economic values were reduced in value.

Different cost conditions were also considered at Janamba Croc Farm. When operating costs were increased by 5 per cent (Table 5), as expected, profit became most sensitive to increases in feed costs, which Treadwell *et al*. (1991) had indicated were the main components of the operating costs. The relative importance of the economic values was not greatly affected by increases in any of the operating costs.

It was reported in Manolis *et al*. (2000) that the shortage of first-grade skins was a major problem faced by the industry. We used an estimate of 45 per cent first-grade skins. This was varied by 5, 10, 20, and 30 percentage points in Table 6. The key result was that, when the proportion of first-grade skins increased by 20 and 30 percentage points, it became profitable to keep

Table 5 Economic values and contributions to aggregate breeding value (figures in brackets) of traits under increased production cost conditions

	Profit per breeding pair ($A)	Economic values					Re-optimised slaughter age
		NoHatch	SlautAge	Surv	FeedCons	%First	
Labour costs							
+5%	910.78	29.15 (0.12)	112.19 (0.44)	29.15 (0.12)	4.75 (0.02)	77.84 (0.31)	140.69
Feed costs							
+5%	873.99	27.97 (0.11)	113.17 (0.45)	29.75 (0.12)	4.98 (0.02)	77.84 (0.31)	140.69
Operating costs							
+5%	982.41	31.44 (0.12)	111.76 (0.44)	29.89 (0.12)	4.75 (0.02)	77.84 (0.30)	140.69

Table 6 Economic values and contributions to aggregate breeding value (figures in brackets) of traits with different proportions of first-grade skins

	Optimal slaughter age (weeks)	Profit per breeding pair ($A)	Economic values					Re-optimised slaughter age
			NoHatch	SlautAge	Surv	FeedCons	%First	
Change % 1st-grade skins								
+5%	141.57	1409.33	45.10 (0.17)	107.17 (0.41)	34.33 (0.13)	4.75 (0.02)	72.82 (0.28)	140.69
–5%	141.57	631.71	20.21 (0.08)	115.16 (0.48)	26.25 (0.11)	4.75 (0.02)	74.33 (0.31)	140.69
+10%	141.57	1772.48	56.72 (0.20)	102.42 (0.37)	38.11 (0.14)	4.75 (0.02)	77.61 (0.28)	140.69
+20%	159.50	2600.78	83.23 (0.21)	126.74 (0.32)	56.13 (0.14)	5.33 (0.01)	122.13 (0.31)	158.51
+30%	159.50	3929.69	121.90 (0.28)	109.71 (0.25)	70.93 (0.16)	5.33 (0.01)	122.80 (0.29)	159.00

juveniles in the system longer, in order to reach the +40 cm belly widths and accompanying higher price brackets.

The belly width function in Equation (9) was simulated to reflect a representative juvenile at Janamba Croc Farm. Parameters c and b were adjusted to simulate alternative growth rates and hatching lengths as the primary determinants of the time taken to reach 35 cm belly widths in Table 7. Increasing the growth rate by 3 per cent increased profit per breeding pair to over $A1500, as juveniles slaughtered earlier had a higher proportion of first-grade skins, and incurred lower production costs. Optimal slaughter age was also reduced to 136 weeks. Decreasing growth rates by 3 per cent increased operating costs per juvenile and reduced average price. Increasing hatching length by 8 per cent had a more extreme impact on profit per breeding pair and optimal slaughter age.

Table 7 Economic values and contributions to aggregate breeding value (figures in brackets) of traits under alternate growth parameters

	Optimal slaughter age (weeks)	Profit per breeding pair ($A)	Economic values					Re-optimised slaughter age
			NoHatch	SlautAge	Surv	FeedCons	%First	
Growth rates								
+3%	137.28	1536.89	49.18	105.07	33.88	4.62	73.68	136.45
			(0.18)	(0.39)	(0.13)	(0.02)	(0.28)	
–3%	146.13	447.66	14.32	118.28	25.80	4.91	81.76	145.2
			(0.06)	(0.48)	(0.11)	(0.02)	(0.33)	
Hatching length								
+7%	136.13	1669.98	53.44	106.15	34.73	4.59	72.49	135.28
			(0.20)	(0.39)	(0.13)	(0.02)	(0.27)	
–7%	146.57	408.45	13.07	115.97	25.52	4.91	82.1	145.66
			(0.05)	(0.48)	(0.11)	(0.02)	(0.34)	

We can conclude from the sensitivity analyses that the economic values estimated in the base case are seemingly stable for small changes in the production and marketing conditions. Moreover, it is evident from the results that farm profit can be increased through the selection of genetically superior breeding animals, particularly with regard to superiority in the selection objectives aimed at improving growth rates, the percentage of skins that are first-grade, and the number of viable hatchlings per clutch.

6. Discussion

In this paper, we modelled genetic improvement as a change or shift in the slopes of simulated biological functions describing crocodile growth, survival, rate of feed consumption, and the proportions of skins in each grade over time. Profit was maximised with respect to slaughter age, and then re-optimised after genetic improvement to allow producers to take advantage of superior juveniles. The driver of this re-optimisation was the pricing regime in the market for crocodilian skins, which awards higher prices for first-grade skins within larger belly width ranges. Because the proportion of skins that were first-grade was simulated to decline with age, producers maximised profit by slaughtering juveniles as soon as they reached the price bracket for the 'handbag' market. Otherwise, if juveniles were retained in the production system, the increase in output as juveniles grew failed to compensate for the decline in average price.

The sensitivity analyses tend to support the observation that the economic values are stable for small changes in the production and marketing systems. However, for larger changes, such as 10 per cent and greater increases in the proportion of first-grade skins, the economic values simulated in the base case are likely to compromise the efficiency of the selection index. The consensus is that prices for first-grade saltwater crocodile skins will be stable into the future. However, unforeseen shifts in demand, such as a backlash against animal leather by consumers, might drastically reduce the prices of crocodile skins. When the implications of a more significant demand shift are combined with the sensitivity of economic profit to exchange rate appreciations and the proportion of first-grade skins produced, industry vulnerability becomes evident. This is further compounded by the heavy dependence of the crocodile industry on fashion-based demand for crocodile leather, as the end use of skins is essentially confined to the manufacture of luxury leather items. Notwithstanding this, the economic values reported here can aid in the establishment of a breeding stock that better meet the needs of producers.

An issue facing the Australian saltwater crocodile industry is the feasibility of the genetic improvement program. Before such programs are undertaken, it is necessary to determine if the program is in the best interest of the farm. A cost–benefit analysis may be used to compare the costs and benefits of the breeding program with those associated with the normal operations of the farm. The costs associated with normal farm operations include the costs of obtaining replacement breeders. The additional costs incurred through the genetic improvement program include the measurement costs, as the economic values do not provide information on the costs associated with achieving the desired genetic change (Goddard 1998). There are also costs associated with maintaining the future breeders until they reach sexual maturity. The benefits associated with the genetic improvement program are the lower production costs and augmented income stream from increased productivity, and possibly from more first-grade skins. By comparing the two scenarios over a suitable time period, it would be possible to determine whether or not it is in a farm's best interest to invest in a genetic improvement program.

There are some limitations in our analysis. Smith (1983) stresses that whole lifetime productive efficiency should be considered when defining the breeding objective. If an important trait is left out, the likelihood that index efficiency is compromised increases. Traits related to meat production were not included as selection objectives, as meat is currently regarded as a by-product of skin production. However, their inclusion may induce a movement toward saltwater crocodiles as dual-purpose production units, and lessen reliance on the markets for skins. The selection objectives predominantly relate to the production side of the saltwater crocodile industry, as they aim to reduce production costs and increase output. They do not specifically address end-user concerns, in this instance, the fashion industry, beyond the shortage of first-grade skins, nor do they anticipate future market conditions by addressing skin quality beyond the absence of blemishes. MacNamara *et al.* (2003) suggest that the Hermes tannery will grade harder when supply reached 15 000 skins per annum, and that price levels would be affected when supply reached 20 000 skins per annum. Thus, selection objectives that reward the superior skins within a grade with a premium, and discount borderline skins, would prepare producers for stricter grading specifications.

A further limitation is that the biological functions are specified independent of one another. This is a significant simplification, as we would expect that, for example, improved growth rates would require increased feed intake. We have also ignored the effect of feed quality and composition on growth rates, survival and skin quality. This second limitation reflects on-farm management. If, for example, a feed source is developed commercially to meet the nutritional requirements of juvenile saltwater crocodiles, similar to traditional livestock industries, the economic values presented here may need revision. Further research into Australian saltwater crocodile economic values may include developing a more sophisticated empirical model that captures the complexity of saltwater crocodile productive biology.

7. Concluding comments

As members of an emerging industry, Australian saltwater crocodile skin producers face a number of constraints that hinder the further development of the industry. The characteristics of saltwater crocodiles distinguishing them as production units impose costs on producers, and may reduce farm profitability. Technical change, through genetic improvement, provides the means by which producers can improve the quality of their stock. Through the use of biological functions that describe juvenile growth within a profit-maximisation framework, the true value of genetic improvement in saltwater crocodiles might be more closely approximated. The economic values reported here indicate that producers should direct selection toward genetic improvement that reduces slaughter age, increases the percentage of first-grade skins, and increases the number of viable hatchlings per clutch. However, it should be noted that the true value of a selection objective also depends on the genetic gain from selection – that is, its estimated breeding value.

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