Environmental Conservation **28** (1): 76–85 © 2001 Foundation for Environmental Conservation

The dynamics of avicultural markets

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Date submitted: 5 May 2000 Date accepted: 20 October 2000

Summary

Trade restrictions stemming from the Convention on International Trade in Endangered Species (CITES) have created a situation in which rare and attractive bird species command high prices on international pet markets. Most of these species are of tropical or subtropical origin, and many are amenable to captive breeding. Hence, the possibility of exporting birds under CITES provisions for the export of captive-raised animals is under debate in many countries around the world. If export bans are replaced by systems of export permits, the economics of avicultural markets will govern the magnitude, timing, and nature of the impacts of the bird trade. Avicultural economics, however, is little studied, and the long-term economic viabilities of exotic pet markets are poorly understood. In order to elucidate these, a dynamic model of an avicultural market was constructed, based on descriptive information. Model simulations showed that the high prices commanded by sought-after bird species tended to bring about oversupply and rapid price decline. Short-lived, fecund species produced a rapid, sharp pulse of oversupply; longer-lived species produced more persistent but less acute conditions of oversupply. The present high prices for protected bird species may be regarded as a potential source of windfall profits, or as a factor that might be manipulated to discourage the poaching and smuggling of wild birds. If export-oriented aviculture is considered as a component of strategies for diversification of agriculture and promotion of sustainable development, it is important that decision-makers factor in the likelihood of significant declines in bird prices and that they consider the risk of accidental species introductions that is inherent in holding large exotic-bird populations.

Keywords: exotic pet, market, aviculture, model, economic risk

Introduction

The Convention on International Trade in Endangered Species (CITES) has protected many charismatic bird species from international trade. These species often command high prices in the pet trade away from their land of origin. For example, a galah (*Cacatua roseicapilla*) selling for US$ 20–60 in Australia (A$ 35–100; A$ 1 = US$ 0.60, July 2000) might sell for 20 to100 times as much on international markets.

CITES does not entirely ban commercial trade in plants and animals that it lists as threatened with extinction (listed in Appendix I of the CITES convention) or potentially threatened with extinction (listed in Appendix II of the CITES Convention). It does, however, place stringent controls on the export of listed animals (Wijnstekers 2000). CITES restrictions have been amplified by national laws in many nations (Favre 1989), including outright bans on commercial wildlife export in countries such as Australia and Brazil. Counter-pressure is mounting in many parts of the world. In Australia, for example, there has been considerable discussion of legalizing the controlled export of native bird species.

What sort of a market might result from widespread commercial production of protected bird species for international pet markets? Is it, as some advocate (RRA&T 1998), a potential source of extra income for struggling rural and regional economies? Or might activities that are ecologically sustainable prove economically fragile?

Little has been published on the economics of the bird trade. The flow of threatened and endangered bird species from the wild into pet markets has been studied widely in conjunction with CITES (Roet *et al.* 1980; Roet & Milliken 1985; Thomsen & Brautigam 1991). Such studies tend to be bird-centred, and rarely provide information on the economic actors and their behaviour.

Although data are scarce, the attributes of bird markets are sufficiently well known to support qualitative description of system behaviour and heuristic modelling. In the Australian (J.M. Robinson, personal observation) and African (M. Perrin, personal communication, August 2000) cases, salient system features include the following four.

(1) Markets with low barriers to entry and strong participation of informal producers. For many breeders, raising birds is a hobby that brings in a few dollars and occasionally pays for itself. Backyard aviaries are numerous, and the line between the producer and the consumer is fuzzy.
(2) Strong market differentiation. In Australia, at least 70 native parrot species and an additional 50 exotic parrot species are traded (Parrot Society of Australia Inc. 1999*a*); in South Africa, around 20 African parrot species and 50 exotic species are traded. (M. Perrin, personal

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communication 2000). Prices range from around US$ 5 for common species (for example 'budgies', *Melopsittacus undulatus*, and peach-faced lovebirds, *Agapornis roseicollis*) to figures in excess of US$ 10 000 for rare and spectacular species of cockatoo in Africa and macaw in both Africa and Australia (Parrot Society of Australia Inc. 1999*a*; M. Perrin, personal communication, August 2000). The difficulty of keeping spans a similar range. Budgies and lovebirds are easily kept as house pets, survive on a diet of birdseed and simple supplements, and given a small aviary, nesting boxes, and two or more pairs of birds, reproduce prolifically. Untrained, parent-raised birds are popular and relatively trouble-free pets. Large macaws and cockatoos, at the other extreme, are notorious shriekers, vigorous chewers, and demand lots of attention (Giannini 1993). For proper socialization, they require careful hand feeding for many months. If not properly socialized and cared for, they tend to develop behaviours such as screaming, biting, and obsessive begging that make them very poor companions (Wilson 1998).

(3) Small niche markets, especially for expensive and difficult to keep species. According to data from the 1998 Australian National Exotic Bird Registration Scheme, there were 640 macaws of 10 species registered in Australia (Parrot Society of Australia Inc. 1999*b*; Table 1). On average (calculated from data in Table 1), each bird holder had just over three birds of the same species.

(4) Supply and demand are modulated by population dynamics. For species that take years to reach sexual maturity, breeding up in response to increased demand may take several years. Demand is easily satiated, because, barring disease, accidents and euthanasia, pet birds are what economists call 'durable'. The potential life span of a large parrot is similar to that of a human being (Wilson 1998), and medium-sized parrots can survive for a few decades (Clubb 1998).

Scattered data are available on birds as pets. For example, a 1998 survey found that around 17% of Australian households kept one or more pet birds (PIAS 1998). The equivalent figure for the USA in 1996–7 was around 8% (AVMA 1997). It is thought that the number of captive birds in the USA is growing by around 5% per year (Meyers 1998). In Australia, the National Exotic Bird Registration Scheme (1998) provides information on the captive populations of many exotic species, but because the earliest data available are from 1997, the data are of limited value for studying trends. In general, demographic data on pet birds are very difficult to obtain (Clubb 1998), as are data on the amount of time for which birds of various species are held as pets and the rates at which they are released to the wild, put into rescue shelters, or die prematurely through neglect, abuse, or euthanasia. Likewise, data on factors such as price elasticity of demand for bird purchases, cross-price elasticities between species, and market response to external events, are virtually non-existent.

This paper describes AviMod, a heuristic model built to explore the potential economic outcomes of recommencing trade in aviary-raised stock for species that are presently withheld from international trade under the CITES convention. It should be emphasized that AviMod is a conceptual model, constructed to yield better understanding of the dynamic features of avicultural markets. It recognizes only one bird species and makes no attempt to model changes in consumer preference or substitution effects.

Method

The model

AviMod was constructed in Stella II version 2.2.1 (Richmond & Peterson 1992). An equation listing is provided in Appendix 1. AviMod resembles other system-dynamics livestock models (for example Meadows 1970; Picardi 1975), in that it tracks livestock demographic processes and relates the supply of livestock to the breeding population, reproductive success, and the environment. It resembles Picardi's (1975) Sahel model in that livestock are kept to satisfy social needs; in this case, the need was that of animal lovers for companion animals. It resembles Meadows' (1970) commodity cycle model (a nonlinear, finite-difference 'cobweb model'; Baumol 1959) in that a population of animals is used for commercial breeding, and herd (or flock) management is modulated by prices. It differs from the Meadows (1970) and other cobweb-

Table 1 Macaws registered with the Australian National Exotic Bird Registration Scheme as of March 1998 (National Exotic Bird Registration Scheme 1998) and prices for the listed species (Parrot Society of Australia Inc. 1999*a*).

Species	*Common name*	*Number of birds*	*Number of holders*	Price (A$ per pair/young bird)
Ara ambigua	Great green macaw	4	1	unlisted
Ara araruana	Blue and gold macaw	301	120	17000/6500
Ara auricollis	Yellow-collared macaw	14	3	unlisted
Ara chloropterus	Green-winged macaw	81	30	25000/10000
Ara macao	Scarlet macaw	125	44	25000/10000
Ara manilata	Red-bellied macaw	6	1	unlisted
Ara maracana	Blue-winged macaw	12	3	unlisted
Ara nobilis	Red-shouldered macaw	73	16	unlisted
Ara rubrogenus	Red-fronted macaw	11	4	unlisted
Ara severa	Chestnut-fronted macaw	11	4	unlisted

type models in that consumers keep the 'product' (pet birds) for years rather than consuming it. It differs from both Meadows (1970) and Picardi (1975) in that animals move between reproducing (commercial) and non-reproducing (pet) populations, depending on price.

Population dynamics

AviMod includes five state variables, namely young birds held by aviculturalists (chicks), young pets, breeding birds (breeders), mature pets, and old birds. The biological side of the model tracks egg laying by breeders, growth of chicks to breeding age, growth of breeders to old age, and mortality of birds of all ages. It is assumed that pets do not breed, and that birds that survive past reproductive age satisfy the demand of bird lovers for pets (in effect, their presence dampens the market). In practice, little is known about the fate of post-reproductive birds in aviculture (Clubb 1998). The assumption made here is based on personal observation, but may not pertain where aviculture is highly commercialized. In AviMod, the numbers of post-reproductive birds are generally small, and this assumption has little effect on model outcomes. Time to maturity, clutch size, and mortality rates are specified externally, and may be altered to describe different species. High prices increase the fraction of eggs that hatch and mature, thus providing a representation of the effects of artificial incubation and other measures to increase reproductive rates.

Both chicks and breeders may be sold to the pet market. The quantities that are sold depend on price. Chicks are more likely to be sold than breeders. If prices are high, pets may be returned to the breeding pool.

The system's temporal behaviour is governed by one positive feedback loop. More breeding birds lay more eggs, which hatch to produce more breeders. This is restrained by several negative feedback loops (Fig. 1). Supply response to demand is delayed by the time it takes for a chick to reach breeding age.

Demand side and price

The number of bird lovers is specified outside the model, and may be varied to look at growing or shrinking demand, or

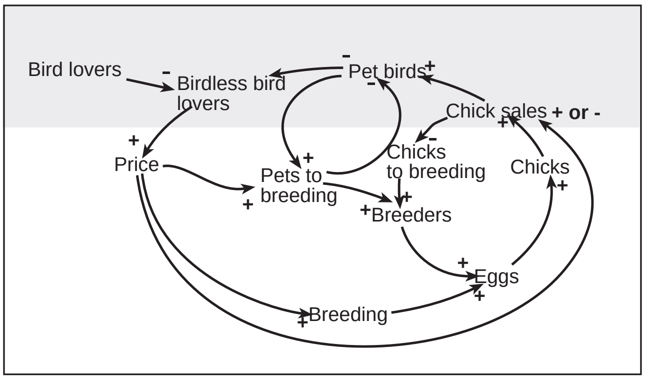


Figure 1 AviMod's main feedback loops.

increased stepwise to look at the opening of new markets. Demand is assumed to be proportional to the fraction of bird lovers who do not have birds.

Price is a function of how well the available supply of chicks covers the unsatisfied demand for pet birds or the extent to which the number of birds held exceeds demand (functional form shown in Fig. 2*a*). Prices are in arbitrary units, scaled in such a way that aviculturalists reduce their breeding stock and cut production when price falls below one.

Supply feedback

If prices are high, producers respond in three ways:

(1) Investing to ensure that a high fraction of the eggs laid hatch into chicks, for example, through use of inubators, and in the model this is accomplished through a price multiplier on breeding (Fig. 2*b*);
(2) Bringing birds from the pet pool into breeding (this could represent either purchase of pets by commercial interests, or hobbyists going commercial), in other words, price pull (Fig. 2*c*); and
(3) Retaining chicks to be used as breeders, in other words, juvenile fraction sold (Fig. 2*e*).

Conversely, if prices are low, breeding birds enter the pet population (price push in Fig. 2*d*), fewer chicks are hatched per breeding pair, and few chicks are retained for breeding purposes.

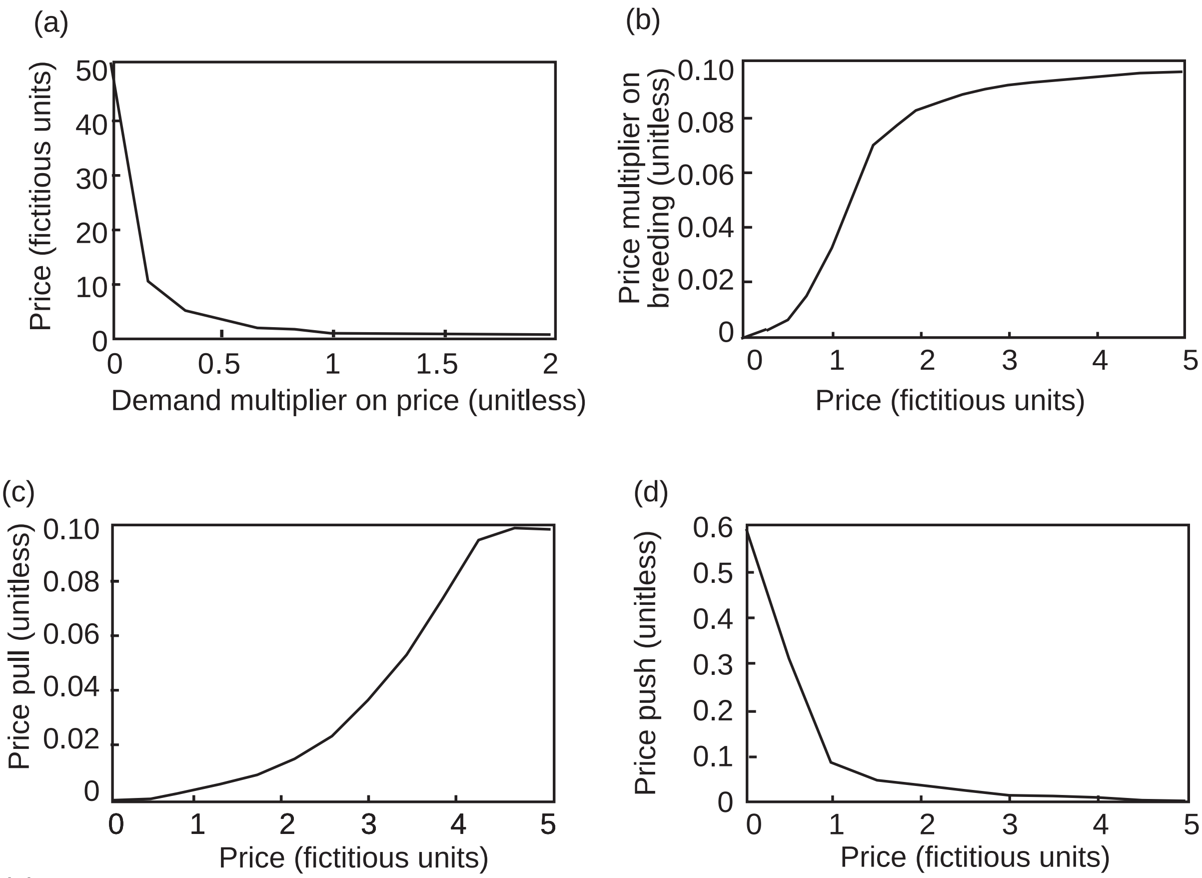
Scenarios

Many model parameters can be altered to study system sensitivity. As a base set of scenarios, I parameterized AviMod to represent three demographic types, namely (1) a budgie-like species of short-lived, fecund bird, (2) a population of birds, such as the medium-sized parrots, with medium life spans and fecundity, and (3) a population of slow-maturing birds with low reproductive rates, representative of cockatoos or macaws (Table 2). Each bird population was assumed to have a target market of 10 000 bird-lovers, each aiming for one bird. All simulations began with a breeding bird population of 1000 birds and an initial number of chicks equal to the number of breeding birds multiplied by the clutch size divided by three, in other words, 333 times the clutch size. Initial values of pets and old birds were set to zero.

Several variations on this base model were tried, all parameterized for Type 2 (the medium-life span group in Table 2) demography. First, a one-year exponential lag (SMOOTH3) was introduced in the relationship between breeding decisions and price to represent the likely scenario

Table 2 Demographic types considered in model scenarios.

Attribute	*Type*		
	1	2	3
Clutch size	8	4	1
Fertile lifespan (yr)	5	12	30
Time to mature (yr)	0.5	2	5



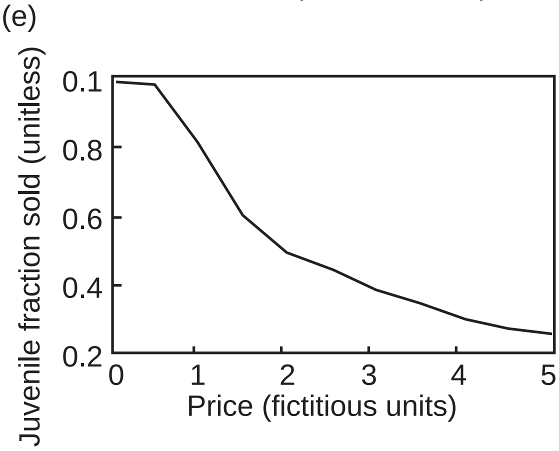


Figure 2 Functional relationships assumed in AviMod as piece-wise linear functions. Prices are scaled such that producers break even at a price of one. All other variables are unit-less multipliers: (*a*) response of price to fraction of demand covered, (*b*) fractional elasticity of bird breeding to price, (*c*) price elasticity factor for sales of pets into the breeding pool, (*d*) price elasticity of transfer of breeders to the pet pool, and (*e*) price elasticity of sale of juveniles as pets.

that producers make their breeding decisions based on the previous year's prices. Second, transfers between pets and breeders were set to zero, representing a situation that is likely to come about in an environment where breeding is highly regulated, or where sales are made to customers in environments where breeding is difficult. Third, to gain insight into the possible effects of removing export restrictions, the consequences of a ten-fold expansion in the number of bird lovers was considered.

After a first round of model testing, inquiries were made over internet newsgroups to determine whether the tendency to oversupply was an observed phenomenon. This turned up reports that bird sanctuaries are growing explosively in the USA, echoing the rapid growth of parrot ownership through the 1980s and 1990s. For example, the Director of the Oasis Sanctuary Foundation wrote (S. Erden, personal communication March 2000): 'We are literally being flooded with throw-away birds.' Bird sanctuaries include many common species, such as cockatiels, but also endangered species such as Moluccan cockatoos.

To study the dynamics of unwanted pet birds, I created a structural variant in which a portion of the mature and old bird populations was transferred to bird sanctuaries, and looked at the growth of sanctuary populations, where 'sanctuary' may be taken at face value or taken as a euphemism for euthanasia.

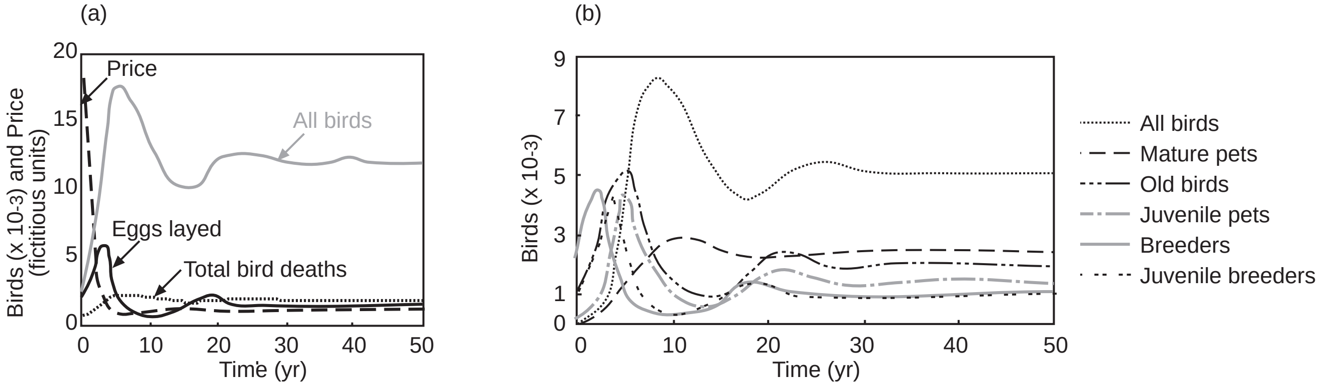


Figure 3 Fifty-year run of base-case scenario with a species with a clutch size of four, that takes two years to reach sexual maturity and has a fertile life span of 12 years (Type 2 in Table 2). (*a*) Summary statistics, and (*b*) disaggregated by population group.

Results

AviMod's structure makes it highly price-responsive. However, particularly for Type 3 species, it takes years for producer decisions to affect supply. If the model is run from an initial state with a large, unmet demand for pets, the populations of breeders and pets begins to expand rapidly (Fig. 3). After a few bird generations, prices fall rapidly. In the low-price environment, breeding birds are sold to the pet trade. As populations age, death rates rise, and eventually the rate at which birds die exceeds the rate at which eggs hatch. Thus both pet and breeder populations decline. This leads to a modest rebound in prices around year 20 which sets off a new, relatively weak demographic wave. By year 50, prices have stabilized at a level that stimulates the breeding of enough birds to replace the birds that die, but no more.

Demographic types

Altering demographic parameters changes the amplitude and timing of market swings, but does not change the underlying behaviour (Fig. 4). Type 1 (budgie type, Table 2) breeds rapidly, and overshoots demand. Excess supply brings prices down to the range that begins to force producers out of production in the first three years of simulation. The conversion of breeding birds to pets, and retention of few chicks for breeding, reduces bird populations and prices rise slightly. This sets off a second, less intense round of expansion, overproduction, and price decline, which in turn leads to a very muted demographic ripple.

Type 3 (Table 2) takes almost two decades to meet demand. Hence prices stay higher for longer; there is more tendency to bring pets into the breeder population and less tendency to sell off breeders as pets, and demographic ripples are quite mild. The Type 2 (Table 2) population is intermediate between Types 1 and 2 in amplitude and timing.

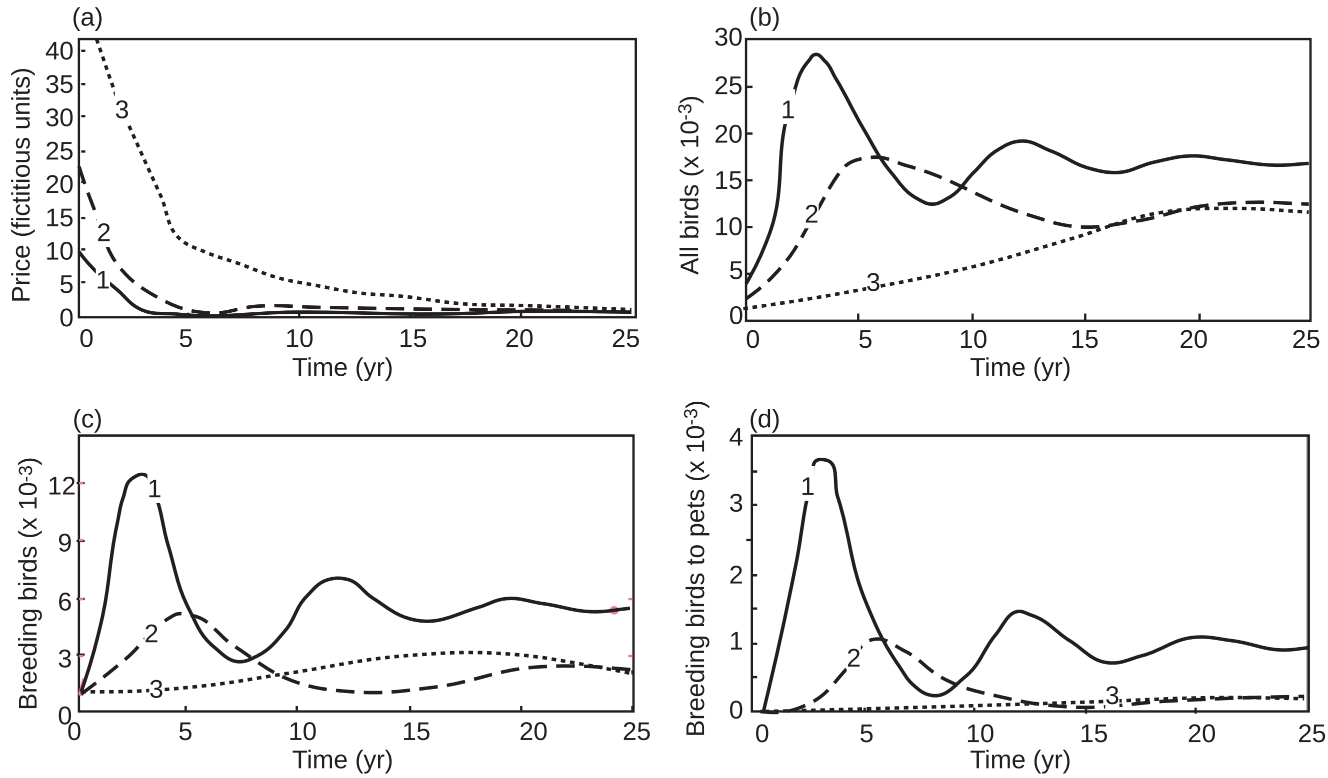
Delayed price information

AviMod's structure implicitly assumes that aviculturalists make breeding decisions based on current price information. This may not happen, either because price information trickles back to producers, or because they are locked into decisions made in a previous season. The model structure was changed so that breeding decisions were based on the previous year's prices. This change made the price oscillate along with demographic parameters and increased the amplitude of oscillations in bird numbers (Fig. 5).

Natives versus exotics

If commercial aviculture is to be thought of as an export industry, a decision must be made about whether to raise native or exotic species. Where native species are raised, for example cockatoo species in Australia or macaw species in Brazil, there is a reserve of captive birds that can be called into breeding if demand is strong. Where exotic species are raised, say conures in Australia or cockatoos in Africa, this buffer is not available.

The tradeoff between breeding of native versus exotic species can be studied in AviMod by changing the rates of flow between the pet pool and the breeding pool and by altering the numbers of birds initially held as pets. In general (not shown), simulations showed that the model is sensitive to the initial number of birds in the system. If aviculturalists start out with a breeding stock that makes them able to serve 20% instead of 10% of market demand, prices stay relatively low, high prices persist for less time, and the peak of oversupply is lower. If simulation starts out with a large supply of pet birds that can be called into breeding and model parameterization allows substantial movement of pets into the breeding pool, the effect is much the same as if the model is initialized with large breeding stocks; prices are damped and supply overshoot is less severe. Stopping the sale of breeders to the pet trade, on the other hand, has little effect on system



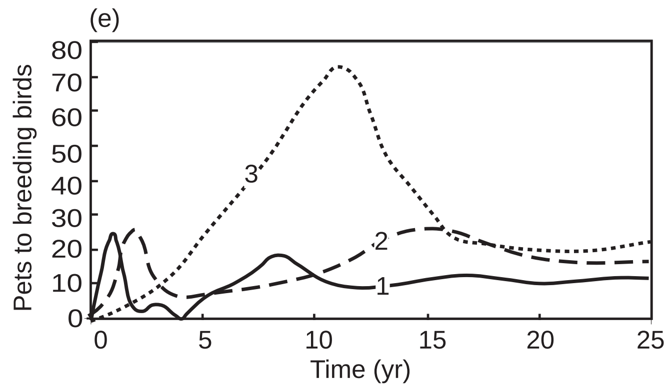


Figure 4 Comparison of performances of different demographic types over 25 years of simulation. Curve numbers correspond to demographic types with long (Type 1), short (Type 3), and intermediate (Type 2) life spans, as given in Table 2, for (*a*) price (fictitious units), (*b*) all birds, (*c*) breeding birds, (*d*) transfer of breeders to the pet pool, and (*e*) transfer of birds to the breeding pool.

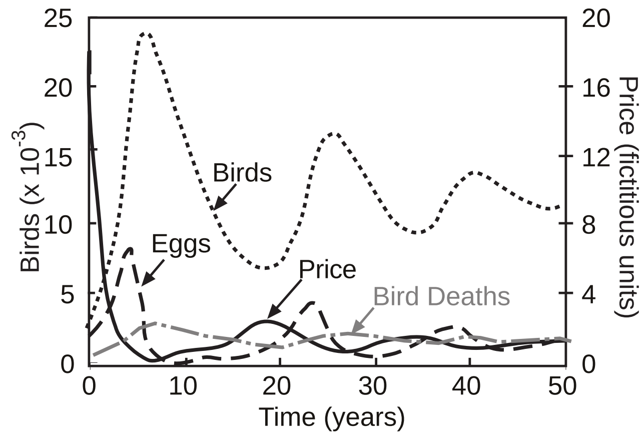


Figure 5 The effect of breeding decisions being based on the previous year's prices. The model was parameterized for a Type 2 species (medium fecundity and intermediate life span).

behaviour, so long as breeders reduce their production of chicks when prices are low.

Opening of new markets

In Australia, and presumably other tropical countries, the most interesting avicultural opportunity comes from development of breeding programmes that conform to CITES requirements, and the relaxation of bans on the export trade. This scenario was approximated in AviMod by expanding the population of bird lovers step-wise, from 10 000 to 100 000, with the full increase coming in one time step. The model was run for 50 years prior to the increase, by which time it had come to an equilibrium state. The sudden increase in demand leads to sky-rocketing prices and to breedering birds laying at near full capacity (Fig. 6). The pulse, however, is short-lived. It takes less than a decade for supply to catch up with demand and bring prices down to the break-even point.

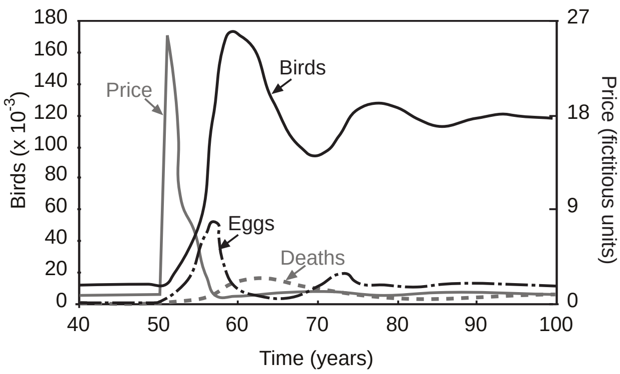


Figure 6 Consequences of an expansion of the market from 10 000 to 100 000 bird lovers. Model was run for 50 years and then market was expanded step-wise and run for an additional 40 years. Only the last 50 years of simulation is shown.

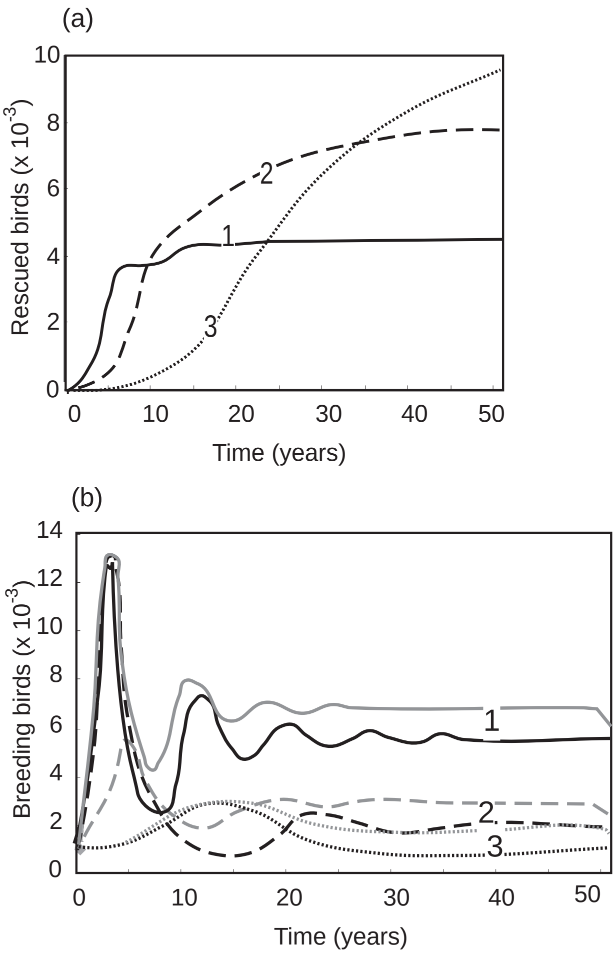


Figure 7 AviMod with 10% of mature pets and old birds being put in rescue each year. Numbers on curves consistent with demographic types given in Table 2. (*a*) Numbers of birds in rescue shelters, and (*b*) comparison of the populations of breeding birds with (grey) and without (black) rescue.

Abandonment and rescue

To explore the dynamics of bird surpluses and the implications for abandonment and rescue, it was assumed that, on average, birds were kept as pets for 10 years, and then turned over to a shelter. Short-lived (Type 1) species are the first to start flooding shelters, but ultimately, the longer-lived birds (Types 2 and 3), the life spans of which often exceed their owners' interest (or life span), pose a greater problem from the perspective of overpopulation and humane treatment of homeless animals (Fig. 7).

Discussion

Caveats

AviMod is a structural cartoon that greatly simplifies a complex reality. There are several places where simplifying assumptions are likely to influence outcomes. First, the model simply seeks an equilibrium price, and does not provide realistic accounting for costs and profits. AviMod's results do not exclude the possibility that equilibrium prices for healthy, well-socialized young birds reflect the value added by careful breeding, hand-feeding, and training. Thus, even 'low' prices may provide employment opportunities in developing countries. Nor does it exclude the possibility that producers can perpetuate the windfall of novelty markets by shifting from species to species and pulling out when the market shows signs of turning downward.

Second, start-up questions are ignored. Establishing a commercial breeding operation for a new species requires the finding of productive breeding stock, the perfection of nutritional and breeding and chick-rearing techniques, and the development of marketing capability. This is likely to be a gradual process taking many years. Hence, a regime of low supply and high prices may persist for a much longer time than indicated in the model, and early market entrants, who come into production while prices remain high, may reap much greater gains than late market entrants.

Third, model structure does not adequately differentiate between styles of production. Little has been published on the structures of the organizations that produce pet birds. These range from well-capitalized operations with much experience working with complex markets and government regulations, to rural producers who have suffered from low commodity prices and consider aviculture as a possible means of diversifying production; to hobbyists whose sell a few birds on the side to cover some of the costs of their hobby. Different types of producer are likely to fare differently in international pet markets, and measures to assist small producers may affect distributional outcomes.

Economic implications

Results from AviMod suggest that if there are no serious impediments to entry into avicultural industries, the market will bring the system from a situation of high profits to a position of oversupply and probable losses, leading to an equilibrium position with low profit margins. The severity of the oversupply and losses is likely to be much greater for fecund, short-lived species; the duration of healthy profits is likely to be longer for species with small broods and long life spans. The inherent problem is system structure; demography delays the producers' response to price. The interaction between formal and informal producers may affect the way the problem develops, but does not affect the root problem.

Boom and bust dynamics have been observed for many species and locations. For example, use of captive breeding to deliberately reduce the market price for Naretha Blue Bonnets *(Psephotus haematogaster* narethae) in Australia achieved greater than a 50% price reduction in three years (Mawson 1999). In the USA in the early 1990s, the wholesale price for a blue and gold macaw (*Ara araruana*) was around US$ 2000; in 2000, the same bird would cost US$ 500–650. African grey parrots (*Psittacus erithacus*) have, likewise, fallen from US$ 1800 to US$ 650 (S. Erden, personal communication March 2000).

Market expansion, for example through relaxation of CITES-related trade bans, only postpones oversupply. A larger market does, however, result in more production, and thus more total profit when the market is good, and greater losses when the market is glutted. It also yields more surplus birds. From a conservation (or animal rights) perspective, these surpluses are a major concern, as they represent birds that are most likely to escape or be released to the wild, or to be abused or euthanized in captivity. Anecdotal evidence indicates that the number of abandoned birds has grown rapidly in the last decade (S. Erden, personal communication, March 2000).

Where booms are based on species for which the captive gene pool is narrow, there may be additional problems. For example, Russel Slade writes (R. Slade, personal communication March 2000): 'the BW (bronze wing) parrot has a dangerously low captive gene pool (12 or less distinct genotypes) yet the price has fallen from over US$ 800 to less than US$ 400 in some areas . . . the result is stunted birds, higher clutch mortality rates, etc.'

Simulation results from AviMod also suggest that the information on which producers act is important. Timely understanding of oversupply and price decline produces greater market stability than operation based on outdated price information. Correct anticipation of price decline may reduce over-investment and make price decline more gradual and less ruinous to producers.

Although these conclusions are tentative, they have policy implications. In general, they suggest that it may be more accurate to view the high prices of some CITES-protected species as offering a possible market windfall, but not sustained high profitability. Prices may be high now, but they are likely to drop rapidly once export bans are replaced by export controls. Market-savvy producers who get into the market for a valued species early may make good profits, especially if they know when to pull out of the market, or at least when to change species. Marginal producers who lack the resources to invest in market research are likely to confront flooded markets when they come into full production.

Third, and lastly, they point to the importance of the information on which producers act. Markets are unstable because producers are drawn in with false hope of easy profits. If expectations were more realistic, markets would be more stable. By extension, documenting and publicizing the history of boom and bust in aviculture should reduce the avicultural industry's potential for build up of surplus populations of captive-reared birds.

In sum, any attempt to promote aviculture as a supplement to rural income must pay attention to the dynamics of bird markets. Failure to do so is likely to be economically costly to producers and lead to overpopulation of captive birds, thus increasing the potential for inhumane treatment of animals and for introduction of non-native species into the environment.

Conservation implications

New markets with low barriers to entry are notorious for boom and bust dynamics. In theory, and in observation, the rush into new production niches commonly leads to product surplusses, vicious price competition, and market 'shake-out' that narrows down the field to the most efficient producers and allows producers to expand to sizes that provide good economies of scale. In economic theory, this is well and good. Low prices are also useful from a conservation perspective, as they make it uneconomical to take birds from the wild or smuggle them across international borders.

However, there are several reasons why special consideration is appropriate when the surplus product is live animals. First, scaling up production from a small number of breeding birds is likely to involve inbreeding, and the resulting bird stocks are likely to be unhealthy. This problem was noted above in the case of Pionus species. Avian veterinarians also note widespread problem in strains derived from rare varieties prized as colour mutations (for example lutino strains; Wilson 1998). Competition among those holding rare breeding stock reduces opportunities for cooperative exchange, as, for example, is practised among zoological gardens.

Second, the presence of large stocks of surplus, non-native bird species increases the risk of accidental introductions. If I hold a large supply of expensive birds, it behoves me to invest in keeping them secure. If the price suddenly falls, and I find myself with an unmarketable commodity, I face a hard decision between destroying birds, holding them at a loss, or selling at a loss and further depressing prices. Under these circumstances, an accidental (and perhaps tax deductible) escape could seem like a blessing. Likewise, low shop prices encourage people to purchase a cute baby birds and to dispose of them when they grow up to be noisy, messy, demanding, and expensive, or when they bite one too many times. As the number of escaped birds increases, so does the probability of paired escapees founding a viable feral population.

Acknowledgements

I thank Peter Mawson of Conservation and Land Management of Western Australia for feedback on an early draft of this manuscript, and the editor of this journal, Mike Perrin, and one anonymous reviewer for helpful comments on the most recent draft. I also thank several members of the Association for Parrot Conservation list (APC-LIST) and Neil Hamilton, Curator of Birds at the Perth Zoo, for helpful suggestions on matters relating to parrot conservation, and John Allen of AviArc for alerting me to the lack of understanding of avicultural markets.

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Appendix 1: formal model documentation

Conventions

➪	Rate of Flow	dt	time increment
❒	State Variable	INIT	initial value
t	time	(x,y)	paired (x,y) values in table look-up

Equations

❒ BreedingBIRDS(t) = BreedingBIRDS(t − dt) + (Maturation + Pets2Breeding − BreederDeaths − Breeders2Pets − Ageing) * dt

INIT BreedingBIRDS = DesiredBirds/10

➪ Maturation = JuvBreeder/Time2Mature

➪ Pets2Breeding = MaturePets*PricePull

➪ BreederDeaths = BreedingBIRDS*Mortality

➪ Breeders2Pets = BreedingBIRDS*PricePush

➪ Ageing = BreedingBIRDS/FertileLifeSpan

❐ JuvBreeder(t) = JuvBreeder(t − dt) + (EggsLayed − Maturation − PetChickSales − JuvBreederDeath) * dt
INIT JuvBreeder = BreedingBIRDS*ClutchSize/3

➪ EggsLayed = SMTH3(PriceMultBreeding*BreedingBIRDS/2*ClutchSize,0.5)
➪ Maturation = JuvBreeder/Time2Mature
➪ PetChickSales = JuvBreeder*JuvFractionSold
➪ JuvBreederDeath = JuvBreeder*JuvMort
❐ JuvPets(t) = JuvPets(t − dt) + (PetChickSales − PetMaturation − JuvPetDeath) * dt
INIT JuvPets = 0

➪ PetChickSales = JuvBreeder*JuvFractionSold
➪ PetMaturation = JuvPets/Time2Mature
➪ JuvPetDeath = JuvPets*JuvMort
❐ MaturePets(t) = MaturePets(t − dt) + (PetMaturation + Breeders2Pets − PetAgeing − MaturePetDeaths − Pets2Breeding) * dt
INIT MaturePets = 0

➪ PetMaturation = JuvPets/Time2Mature
➪ Breeders2Pets = BreedingBIRDS*PricePush
➪ PetAgeing = MaturePets/FertileLifeSpan
➪ MaturePetDeaths = MaturePets*Mortality
➪ Pets2Breeding = MaturePets*PricePull
❐ OldBIRDS(t) = OldBIRDS(t − dt) + (PetAgeing + Ageing − OldDeaths) * dt
INIT OldBIRDS = 0

➪ PetAgeing = MaturePets/FertileLifeSpan
➪ Ageing = BreedingBIRDS/FertileLifeSpan
➪ OldDeaths = OldBIRDS*Mortality*AgeMultDeath

AgeMultDeath = 3
BirdLovers = 10000+STEP(0,10) /* variable used in sensitivity testing, increases number of bird lovers
ClutchSize = 4
DesiredBirds = BirdLovers*DesiredBirdsPerCap
DesiredBirdsPerCap = 1
FertileLifeSpan = 12
HealthInCaptivityFactor = 1
JuvMort = .1
Mortality = HealthInCaptivityFactor*1/FertileLifeSpan
Pets = JuvPets+MaturePets+OldBIRDS

Time2Mature = 2
JuvFractionSold = GRAPH(Price)
(0.00, 1.00), (0.5, 0.98), (1.00, 0.815), (1.50, 0.6), (2.00, 0.5), (2.50, 0.445), (3.00, 0.39), (3.50, 0.345), (4.00, 0.305), (4.50, 0.275), (5.00, 0.255)
Price = GRAPH((JuvBreeder+Pets)/DesiredBirds)
(0.00, 50.0), (0.167, 10.0), (0.333, 5.00), (0.5, 3.15), (0.667, 2.00), (0.833, 1.40), (1, 1.00), (1.17, 0.8), (1.33, 0.65), (1.50, 0.6), (1.67, 0.5), (1.83, 0.3), (2.00, 0.2)
PriceMultBreeding = GRAPH(Price)
(0.00, 0.00), (0.25, 0.035), (0.5, 0.07), (0.75, 0.165), (1.00, 0.32), (1.25, 0.56), (1.50, 0.705), (1.75, 0.78), (2.00, 0.83), (2.25, 0.86), (2.50, 0.885), (2.75, 0.91), (3.00, 0.92), (3.25, 0.935), (3.50, 0.94), (3.75, 0.945), (4.00, 0.955), (4.25, 0.96), (4.50, 0.96), (4.75, 0.96), (5.00, 0.96)
PricePull = GRAPH(Price)
(0.00, 0.00), (0.417, 0.00), (0.833, 0.002), (1.25, 0.005), (1.67, 0.0085), (2.08, 0.0145), (2.50, 0.023), (2.92, 0.0355), (3.33, 0.0515), (3.75, 0.074), (4.17, 0.094), (4.58, 0.099), (5.00, 0.0995)
PricePush = GRAPH(Price)
(0.00, 0.6), (0.5, 0.315), (1.00, 0.09), (1.50, 0.0475), (2.00, 0.034), (2.50, 0.025), (3.00, 0.0155), (3.50, 0.01), (4.00, 0.0075), (4.50, 0.0065), (5.00, 0.0055)