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## BRINGING HOME THE BACON: A SPATIAL MODEL OF WILD PIG HUNTING IN SULAWESI, INDONESIA

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**Abstract.** A spatial model is developed for the hunting of two endemic wild pig species, the babirusa and the Sulawesi wild pig, in the northern arm of Sulawesi, Indonesia. The spatial component of the model allows the influences of distance from the end market, road condition, and the distribution of vegetation types to be included into the model. These are all key determinants of the effects of hunting pressure on populations of these species. The model shows that under current economic conditions at equilibrium, the babirusa will be reduced to very small numbers in remote parts of the region, while the Sulawesi wild pig will be less badly affected. Under the conditions pertaining in the 1950s, before major road-building, the two species were much more widespread. The model is used to investigate the effects of various law-enforcement policies on hunting. It is shown that the best way to reduce hunting pressure on the babirusa is to enforce fines for the selling of babirusa meat in the end market. The model is also sensitive to changes in hunters' opportunity costs, showing that if economic conditions in the region improved, the hunting rate would decrease substantially. This is a new application for coupled map lattice models, and one with great potential for the analysis of the population dynamics of other exploited species.

**Key words:** babirusa; bioeconomic model; coupled map lattice; hunting; Indonesia; spatial modelling; Sulawesi wild pig.

### INTRODUCTION

Sulawesi, Indonesia, has two endemic species of wild pig, the babirusa (*Babirusa babirusa*) and the Sulawesi wild pig (*Sus celebensis*). The babirusa is an extraordinary, curly-tusked pig found only in rain forest areas, with a total wild population of  $\approx 5000$  individuals. It has a very limited distribution, being found in only three of Sulawesi's four provinces (and the small neighboring islands of Sula, Buru, and Togian). Densities of the babirusa are believed to be highest in the northern province (MacKinnon 1981). It is officially protected by Indonesian law (Republik Indonesia 1990), which states that it is illegal to hunt, kill, or trade babirusa. The species is undergoing rapid range contraction. Nineteenth century naturalists recorded babirusa at locations in the northern tip of Sulawesi (Wallace 1869, Guillemard 1886, Hikson 1889), while today most babirusa in North Sulawesi are found at the western end of the province. The Sulawesi wild pig is as yet unprotected, and is sympatric with the babirusa, though found at higher densities and also in disturbed areas.

The province of North Sulawesi is a long, narrow arm of land (25 000 km<sup>2</sup>, 600 km in length and, on average, just 50 km wide (Fig. 1). In Minahasa, the district at its northern tip (and location of the provincial capital, Manado) 95% of the population are Christian

and here wild pig meat is extremely popular. The remaining two districts (Bolong Mongondow and Gorontalo) are almost entirely inhabited by Muslim peoples, for whom eating or touching the pig is taboo. Monitoring of the situation in North Sulawesi today has revealed an organized network of hunting and trade in wild pig meat there. Dealers from the district of Minahasa drive to Bolong Mongondow and Gorontalo to purchase wild pig meat from hunters at the forest edge, usually Minahasan people who stay at the forest site specifically to catch wild pigs.

This paper presents a spatial model of babirusa and Sulawesi wild pig harvesting. The position of the roads in the province has a great impact on which areas can be easily reached by the hunters and the dealers, and therefore the profit to be made by catching pigs in an area; it is therefore important that the spatial distribution of the two species is considered. A coupled map lattice was used to model the populations of babirusa and Sulawesi wild pig in each area. Coupled map lattices have been successfully used in other areas of ecology (Hassell et al. 1991, Pacala and Tilman 1994), but the model introduced here has two unusual features: rather than assuming that the underlying physical environment is homogenous, as is usually the case with spatial models, the position of features such as habitat, roads, and the actual shape of North Sulawesi were used as a base for the system. Another example of this is Green (1990). Also, it is the global spatial distributions of pigs and habitat that affect the dynamics of

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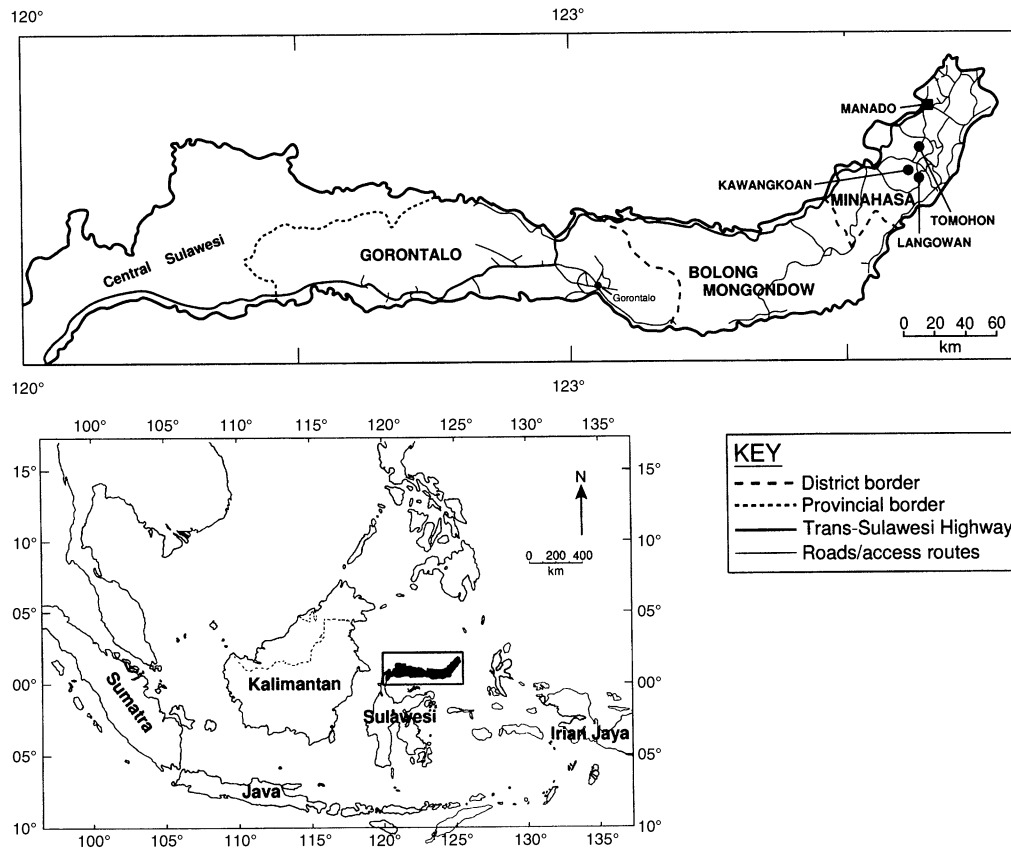


FIG. 1. Map of the northern arm of Sulawesi, showing major towns and regions mentioned in the text.

each cell rather than just a localized neighborhood of sites.

Since the two species are hunted and traded together, a model that includes both species is required in order that the effects of hunting on any one species are correctly assessed. Thus, although the Sulawesi wild pig is not as yet endangered, its population dynamics must be modelled along with those of the babirusa. The model was used to simulate the populations of babirusa and Sulawesi wild pig that would be expected at equilibrium under current physical and economic conditions as well as under previous road conditions. This allows a prediction of the future status of the species should hunting continue unchecked. The effectiveness of various policies for the control of hunting is also examined.

ASSUMPTIONS AND PARAMETER VALUES

The model requires the estimation of both economic and biological parameters, as well as the use of physical parameter values such as the position and condition of roads and the vegetation types in each part of the northern arm of Sulawesi. The vegetation types were obtained from recent maps (Land Resources Development Centre and Bina Program, 1988). The parameter values used are shown in Table 1 and the road system of North

Sulawesi is shown in Fig. 1. Just one road links Minahasa with the Gorontalo region. This road first became passable in 1980, although then it was necessary to raft vehicles across major rivers; it was first fully tarmacked in 1992. In the model, roads have been classified as primary, secondary, and tertiary, based on first-hand experience of most roads in the province, combined with recent maps (Land Resources Development Centre and Bina Program, 1988). Speeds on the roads and the speeds of hunters walking through forests were obtained from personal experience and from discussions with hunters and dealers (Table 1).

Market structure

*Description of the market and harvesting process.*—About 12 dealers, all Minahasan, currently sell wild pig meat (babirusa and Sulawesi wild pig) in the markets of Minahasa, chiefly Langowan, Tomohon, and Kawangkoan (see Fig. 1 for place names). Dealers from these towns drive out every week in small pickup trucks to purchase babirusa and Sulawesi wild pig from hunters. Today they mostly purchase in the Gorontalo district and at the North/Central Sulawesi provincial border, a round trip of up to 1200 km. They purchase this meat at the forest edge or at collection points and carry it back smoked or alive for sale in the weekly market.

TABLE 1. Parameter values for the model under 1995 conditions. (A) Distance-related costs; (B) parameters unrelated to distance. Rp = Rupiah (US\$1 = Rp 2200).

A) Distance-related costs		
Parameter	Travel costs* (Rp/km <sup>2</sup> )	Travel speeds (km <sup>2</sup> /h)
Primary road	182.5	50
Secondary road	207.5	30
Tertiary road	270	15
Walking in forest	225	2
Walking in logged areas	112.5	4
Walking in mountains	300	1.5
B) Parameters unrelated to distance		
Parameter	Value	
Intrinsic rate of increase		
Babirusa	0.35	
Sulawesi wild pig	0.62	
Carrying capacity (no./km <sup>2</sup> )		
Babirusa	1.25	
Sulawesi wild pig	10	
Catchability coefficient		
Babirusa	0.016	
Sulawesi wild pig	0.001	
Price (Rp/individual)		
Babirusa	45 000	
Sulawesi wild pig	40 000	
Time to check a snare (h)	0.25	
Cost of a snare (Rp)	465	
Opportunity costs (Rp/h)		
Dealer	1875	
Hunter	450	

Dealers traditionally have their "own" hunters who regularly supply meat to them. Hunters are typically Minahasans and they hunt singly or in pairs. The dealer transports them from Minahasa to a hunting area where they remain for 2–6 mo at a time to trap wild pigs, before moving to a different forest area. There are currently ≈400 hunters trapping in North Sulawesi province.

Wild pig meat is usually sold smoked by the piece. There is no difference in price per piece between babirusa and Sulawesi wild pig at the market, thus the dealer obtains Rp (Rupiah) 40 000–60 000 for an adult male, Rp 40 000 for an adult female, and Rp 25 000 for an immature (US\$1 = Rp 2200). In the model, we use the average price paid for a pig in the market, which is Rp 45 000 for a babirusa, while the lighter Sulawesi wild pig fetches on average Rp 40 000. Fluctuations in prices of meat per piece are hard to quantify, but the following features have been observed: Dealers give small discounts to their regular customers in the form of extra meat. Toward the end of the selling day they also accept lower prices in order to make a sale: any meat left has also deteriorated in condition by having been displayed in the market since early morning. Slight increases in price per piece occur if wild pig meat is scarce in the market or at particular times of the year such as Christmas.

Hunters are paid in cash by dealers at the forest edge

or at a collection point. Typically dealers purchase animals whole, paying the same price for babirusa and Sulawesi wild pig: adult male Rp 12 500–15 000, adult female Rp 10 000–12 000, immature of either sex ≈Rp 7500 (depending on size). The usual method by which hunters trap wild pigs is using nylon string leg snares set on paths used regularly by the animals, and around wallows, salt-licks, and fruiting trees. Hunters each set 15–50 snares, which are checked usually every 3rd d. Once the hunter is at the forest site, string is only available to him via the dealer, with the cost deducted from the payment for his meat. Hunters spend ≈Rp 100 000 on string in 1 yr.

Minahasan people have a strong preference for wild pig meat compared to domestic pig. At Langowan purchasers can distinguish babirusa from Sulawesi wild pig, but at Tomohon they cannot, although only a small amount of babirusa meat is sold at Tomohon. Sulawesi wild pig is commonly transported alive and butchered on demand in the market. Some babirusa was formerly transported alive but due to recent increased enforcement is now always smoked at the forest to make it less easily distinguishable from Sulawesi wild pig. Other popular meats sold regularly in the markets of Minahasa (listed in broad order of importance) are fresh and dried fish (salt- and freshwater), domestic pig, dog, forest rat, beef, monkey, snake, and cuscus. Wild pig is preferred above all other meats, and is sold in a specific area of the market.

*Assumptions made in the model.*— A key constraint for the dealer is transporting the meat to market before it becomes unsaleable. We assume 4 d as the maximum return journey time from the location of purchase, and that after this time the meat is unsaleable. We also assume a market structure of perfect competition (Begg et al. 1984), both for the dealers selling the meat in the end-markets and for the hunters selling the meat to dealers. The assumption allows us to collapse the model into a single set of incentives, because sellers in a perfectly competitive market at equilibrium make no abnormal profits, and so the price that the dealer must pay to the hunters is equal to the costs incurred by the hunter to supply the meat. Thus the hunters' costs are transferred directly to the dealers, and the model can be run using only the dealers' incentives. The equilibrium condition that sellers make no abnormal profits does not mean that actual profits are zero, however, but that the excess profit made as a wild pig hunter or dealer, over and above that which could be made in the next most profitable industry, tends to zero. This means that people are no longer better off if they move into the wild pig industry, or if they move out of it, because they are making the same profits whatever they do. Thus the market is at equilibrium. This is represented as zero profits, because the analysis uses opportunity costs as the cost of hunters' and dealers' time. These are the wages that the person could have made in the

next most profitable alternative business if they were not working in the wild pig industry.

Under the assumption of perfect competition, firms face a horizontal demand curve: the quantity an individual sells has no effect on the market price. This seems a reasonable assumption for dealers in the wild pig trade at the moment, as data collected in the markets over 3 yr show a constant price despite fluctuations in quantity supplied. However, price invariance to short-term supply fluctuations might not necessarily mean that in the long term, prices might not change due to shortage of wild pig meat as populations decline, or to changes in consumer income or tastes. However, as we have no data on the effects of these long-term factors on prices, it was thought better to assume fixed prices than to further increase the number of untested assumptions in the model.

The main violation of the assumptions of perfect competition is that there are a relatively small number of dealers in the market at present. Only 12 dealers currently travel regularly to Gorontalo to buy wild pig meat, so their individual effect on the industry is not trivial. However, because the road was only fully tarmacked in 1992, the industry is in a state of disequilibrium at the moment, with dealers still entering it and abnormal profits being made. Thus before 1970, only 1 dealer was active, by 1984 there were 3, and now 12 are active. Barriers to entry in the industry do exist since a dealer must have sufficient initial capital to purchase a vehicle (at least 3.3 million rupiah, US\$1500) or to hire one (Rp 165 000, US\$75 per trip). However, given the data from the markets and the ease with which dealers can enter and leave the industry, it is likely that in the longer term perfect competition assumptions would be appropriate. At the hunter level, a horizontal demand curve is a valid assumption since the price of the meat supplied by the hunter is independent of the quantity supplied. A large number of hunters are active and their product is homogenous. A few hunters nowadays keep back meat from dealers who buy per animal to sell to dealers who purchase by kilogram. By doing this they are effectively charging a higher price for their meat. Any person may become a hunter, although hunters do require the collaboration of a dealer to purchase their meat and supply string in order to enter this occupation. There are not a large number of buyers for their meat, this being limited by the number of dealers; however, as stated above, the market is not yet at equilibrium.

On the whole, perfect competition is an adequate simplification of the prevailing market structure, both for hunters and dealers. This assumption is equivalent to open access harvesting. Another assumption that could have been made would be profit maximization. This generally leads to a higher population size for the resource being harvested, how much higher depending on the discount rate of the harvester (Clark 1990). However, this assumption would not be appropriate for

this system, as it requires a single resource owner harvesting as a monopoly, or harvesters acting to maximize joint profits, perhaps in a cartel. Since the only prerequisite for becoming a dealer is the ability to drive along a public road to collect meat, and given the problems with law enforcement in the area, we consider this market structure to be most unlikely to occur.

#### *Harvesting costs*

Costs on primary, secondary, and tertiary roads are calculated in rupiah per kilometer. This includes the cost of gas, vehicle maintenance, and the dealer's time costs. Opportunity costs are used for the time spent hunting or travelling. These represent the implicit wage earned by the hunter or dealer, and are calculated as the wage available in the next most profitable alternative employment. Other occupations open to dealers are trading other goods in markets or small shops, which yields an estimated income of Rp 1875 per hour (US\$0.85). Other occupations open to hunters are agricultural labor or subsistence agriculture, which yields an estimated income of Rp 450 (US\$0.20) per hour. Costs of gas and vehicle maintenance per kilometer are considered to be identical on each type of road, but the dealer's time costs differ according to the speed travelled. Gas costs Rp 700 per liter and a typical dealer's vehicle travels 10 km/L, giving a value of Rp 70/km. Vehicle maintenance is estimated per 1200-km trip, based on the costs for a dealer making 50 trips per year. Tires are changed once every 10 trips at a cost of Rp 280 000. Rp 28 000 is spent on oil every six trips, and every 18 mo the engine is changed at a cost of Rp 600 000, giving an average of Rp 40 664 per trip. To this is added Rp 39 336 as the cost of routine spare parts per trip and Rp 9428 as the amortized cost of the vehicle itself, giving a total maintenance cost per trip of Rp 89 428.

A hunter is estimated to walk at a speed of 2 km/h in rain forest while checking his snares and carrying meat. Since his opportunity costs are Rp 450 per hour his costs in rain forest are Rp 225/km. The hunter is assumed to walk at a speed of 4 km/h on land from which the forest has been cleared. The cost of a snare was calculated from the cost of 1 kg of string (Rp 6500) divided by the number of snares made from this (14). Assuming that one grid square in the model (1 km<sup>2</sup>) contains one trapping location, hunters' information on the number of snares set, the time taken to check the snares, and the time to walk around a grid square are used to obtain an estimate of the time taken to check a single snare.

#### *Biological parameters*

Wild pigs are assumed to live only in forested areas. The intrinsic rates of increase for babirusa and Sulawesi wild pig in forested areas are estimated using Cole's equation (1954) on data collected by the first author and from zoo populations. These estimates are rough

due to the difficulty of obtaining good biological data on the species. Sensitivity analyses presented later in the paper show that the model is relatively insensitive to inaccuracy in the estimation of the intrinsic rate of increase. The carrying capacity of babirusa is approximated from density estimates at the only site where an intensive study of Babirusa has been conducted; the figure of 1.25 is used, calculated from an estimated population of 500 individuals in a 40 000 ha area. The carrying capacity of Sulawesi wild pig is also approximated from density estimates; an estimated value of 10 individuals/km<sup>2</sup> is used, based on research indicating a density of 12 individuals/km<sup>2</sup> at Tangkoko Dua-Saudara Reserve, North Sulawesi, a reserve with a rather higher density of Sulawesi wild pig than is usual (O'Brien and Kinnaird 1996, World Wildlife Fund 1980). The catchability coefficient is the probability of catching one individual in a population at carrying capacity if one snare is put down. This is the least accurately estimated parameter. Information from experienced hunters was used to estimate it. They indicated that 90 snares were needed to catch two Babirusa and one Sulawesi wild pig per week, giving a catchability (normalized by the population density of each species) of 0.016 for babirusa and 0.001 for Sulawesi wild pig. The hunters reported that of the two species babirusa is easier to catch, Sulawesi wild pig being more able to detect and avoid snares. Sensitivity analyses reported later show the effect of changes in this parameter on the model's results.

#### THE SPATIAL MODEL

The implementation of the coupled map lattice involves the discretization of space into a lattice of square cells. The area of the squares could be altered but usually ranged between 0.25 and 4 km; very little quantitative difference was seen over this range, but the speed varied by up to a factor of 16. Five variables were assigned to each cell ( $i, j$ ): the type of habitat to be found at the site  $S_j$  (i.e., sea, major road, minor road, forest, logged, area etc.); the average cost  $C_j$  of trapping and transporting a single pig to market from that site; the number of pigs to be harvested from the site  $H_j$ ; and the population of babirusa  $B_j$  and Sulawesi wild pig  $W_j$ .

Using simple logistic growth, coupled differential Eqs. 1 and 2 can be formed (Clark 1990); from these the number of babirusa and Sulawesi wild pig at equilibrium in each site of suitable habitat can be calculated given the harvesting value  $H$ .

$$\frac{dB}{dt} = r_b B \left(1 - \frac{B}{K_b}\right) - \left(\frac{q_b B}{q_b B + q_w W}\right) H = 0 \quad (1)$$

$$\frac{dW}{dt} = r_w W \left(1 - \frac{W}{K_w}\right) - \left(\frac{q_w W}{q_b B + q_w W}\right) H = 0 \quad (2)$$

where  $r$  is the intrinsic reproductive rate,  $K$  is the carrying capacity, and  $q$  is the catchability coefficient. The

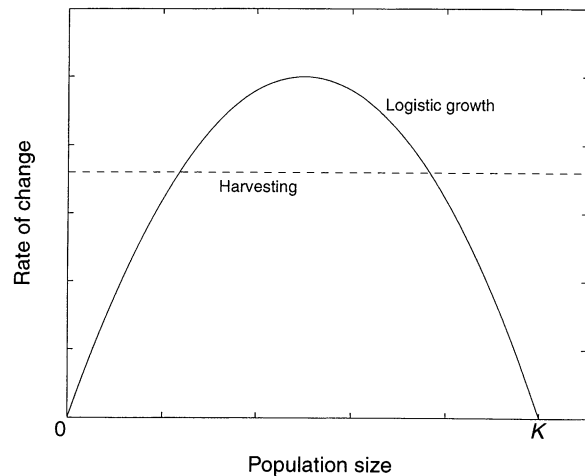


FIG. 2. The rate of change of a population due to logistic growth and harvesting (see Eq. 3).  $K$  = carrying capacity.

subscripts  $b$  and  $w$  refer to the babirusa and Sulawesi wild pig, respectively. This should be compared to a simple harvesting model as explained below.

#### The simple harvesting model

To understand the more complex system outlined above it is helpful to review the behavior of the simple harvesting model:

$$\frac{dX}{dt} = rX \left(1 - \frac{X}{K}\right) - H \quad (3)$$

The rate of change in the population can be viewed as two separate expressions: an increase due to logistic growth and a decrease due to harvesting. For sustainable harvesting it is necessary for these two terms to balance. This is represented in Fig. 2. It is clear from the graph that for small enough harvesting values the harvesting and growth rates balance at two points. The right-hand point is stable to small perturbations, the left-hand point is unstable; perturbations from this point will either lead to extinction or to the right-hand equilibrium. If the harvesting is so large that it lies above the logistic growth curve, then the population will rapidly become extinct. Finally it should be noticed that the maximum sustainable harvesting level corresponds to the maximum in the logistic growth term, which occurs at half the carrying capacity and has a value of  $rK/4$ .

#### The two-species model

Returning to the problem of the population dynamics of the babirusa and Sulawesi wild pig, from Eqs. 1 and 2:

$$\begin{aligned} \frac{H}{q_b B + q_w W} &= \frac{r_b}{q_b} \left(1 - \frac{B}{K_b}\right) = \frac{r_w}{q_w} \left(1 - \frac{W}{K_w}\right) \\ \Rightarrow B &= \left( r_b q_w - r_w q_b + q_b r_w \frac{W}{K_w} \right) \frac{K_b}{r_b q_w} \quad (4) \end{aligned}$$

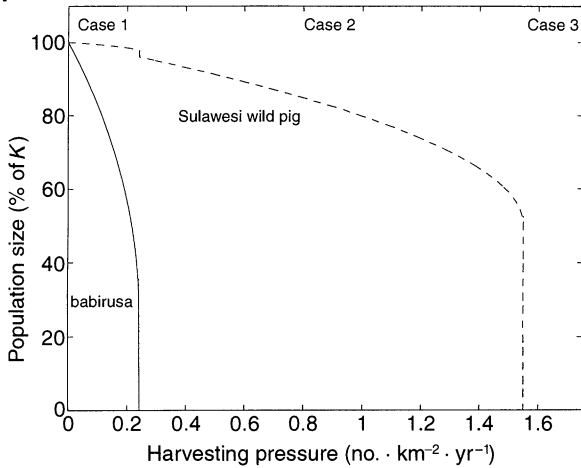


FIG. 3. The populations of babirusa and Sulawesi wild pig as percentages of the carrying capacity ( $K$ ) for various levels of harvesting, using the data in Table 1.

Substituting this into Eq. 2 gives a quadratic form for  $W$  (and similarly for  $B$ ):

$$\left(\frac{r_w q_b^2 K_b}{r_b q_w} + q_w K_w\right)W^2 - K_w\left(\frac{2r_w q_b^2 K_b}{r_b q_w} + q_w K_w - q_b K_b\right)W - K_w^2\left(q_b K_b - \frac{r_w q_b^2 K_b}{r_b q_w} - \frac{q_w H}{r_w}\right) = 0. \quad (5)$$

To run the model, a value is chosen for  $H$  for each site. Then Eq. 5 can be solved, and taking the larger root (which is stable, cf. the simple example above), the value of  $W$  and the value of  $B$  at each site can be found; three scenarios are now possible, which must be interpreted with the biology of the system in mind (Fig. 3):

Case 1. If the solution to Eqs. 4 and 5 leads to both  $W$  and  $B$  being real and positive, then it is possible to harvest at the rate  $H$  and still sustain a population of babirusa and Sulawesi wild pig at the site.

Case 2. If the harvesting is too large to maintain a population of both pig species, then the babirusa will have been driven to extinction first at the site. This is because  $q_b > q_w$ ,  $K_b < K_w$  and  $r_b < r_w$ , implying that the number of babirusa is always less than the number of Sulawesi wild pig. With the babirusa population  $B$  set to zero Eq. 2 becomes:

$$\frac{dW}{dt} = r_w W \left(1 - \frac{W}{K_w}\right) - H = 0.$$

This is the standard harvesting model with logistic growth; the stable solution is:

$$W = \frac{K_w r_w + \sqrt{K_w^2 r_w^2 - 4HK_w r_w}}{2r_w}. \quad (6)$$

If this is real, then only the Sulawesi wild pig remains extant at the site, but a sustainable harvest of  $H$  pigs a year is still possible.

Case 3. If the harvesting is higher still and the so-

lution to Eq. 6 is imaginary, then both the babirusa and the Sulawesi wild pig will be driven to extinction by that level of harvesting, so that  $B = W = 0$  at the site.

If the population of wild pigs at a site remains extant, then  $H$  pigs per year can be harvested from that site and taken to market. The average return per pig at a site is therefore:

$$\text{Return} = \frac{P_b q_b B + P_w q_w W}{q_b B + q_w W}$$

where  $P_b$  and  $P_w$  are the price of babirusa and Sulawesi wild pig, respectively. It is now necessary to calculate whether this level of harvesting is economically viable. The cost  $C_y$  of taking each pig from a site to market is calculated in several parts as follows.

As the density of pigs decreases, then the number of snares it is necessary to set and the amount of time taken checking the snares will increase; thus the costs of trapping a pig escalate as the inverse of the density of pigs. The cost of carrying a pig to the nearest road is a simple linear function of distance, i.e., the time taken to travel to the road times the opportunity costs of the hunter. The cost of transporting the pig to market along the roads by the fastest route is calculated as the total cost of travelling each stretch of road divided by the number of pigs being moved along it. The cost can at most be divided by 100 pigs, as this is the maximum that can be transported in one truck. Finally it is important to consider the amount of time taken to transport the pigs to market, as even after smoking the meat has a limited saleable lifetime of  $\approx 4$  d. Hence, the farther the meat has to be transported the more frequently it must be brought to market. This means that the cost becomes:

$$\text{Cost}' = \text{Cost} \times \frac{4 \text{ d}}{4 \text{ d} - \text{Transport time}}.$$

Now that the cost per pig has been calculated the assumption of perfect competition is used, which implies that profits are zero. The profit per pig at a site is:

$$\text{Profit}_y = \text{Return}_y - \text{Cost}_y.$$

The changes made to the harvesting term in light of the profits depend on whether the population is extinct at the site or not. If the population is extant and the return is greater than the cost, then more pigs can be harvested from an area, so  $H$  is increased by an amount proportional to the profit divided by the return. If, however, the return is lower than the costs, then the harvest is decreased by a similar amount.

If the populations are extinct, then this could be because the profits to be gained are so high that any wild pigs will always be harvested to extinction. If this is so, then the return when  $W = K_w/2$  and  $B = 0$  (sustainable harvesting is greatest, cf. simple model above) will still be greater than the costs, in which case  $H$  is set to the minimum value that causes extinction;  $H_{\min}$

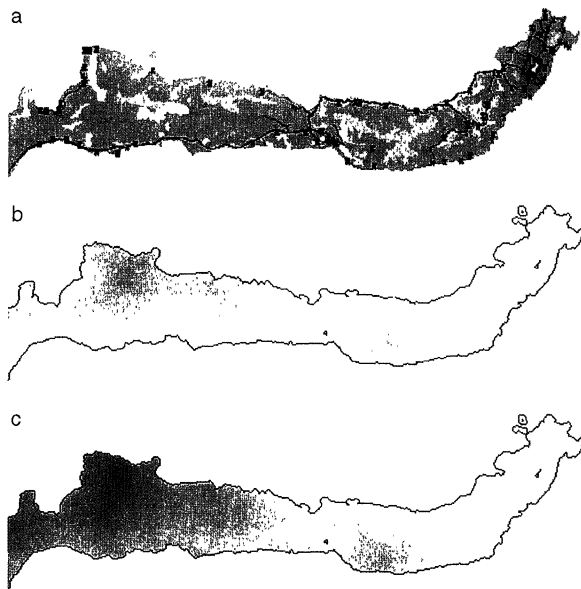


FIG. 4. Input data to the model: (a) the digitized layout of the northern arm of Sulawesi, showing roads and villages; (b) the time taken to get to each point in 1995; and (c) the time taken to get to each point in 1950.

$[=r_w K_w/4]$ ; otherwise  $H$  is set to  $H_{\min}$  minus an amount proportional to the profit divided by the return.

Using this new value of  $H$  for each site the entire procedure is repeated until convergence is obtained. Convergence is usually fairly fast, and after 50–100 iterations the error is small enough to be neglected. It should be noticed that the spatial features are only introduced in terms of the costs of travelling to market, otherwise each cell behaves autonomously, i.e., there is no diffusion of pigs between neighboring sites. The omission of diffusion on a short time scale is justifiable because harvesting varies slowly over space so that each wild pig would experience little or no variation over its usual range. The long-term effects have not been included as this model is concerned with the final equilibrium state, while diffusion has a definite temporal scale, which would vastly complicate the model. It is felt that the inclusion of diffusion would have little effect on the final equilibrium state as this state is strongly attracting and the diffusion is expected to be slow compared to the effects of hunting. Any effect observed is likely to be a slight reduction in final numbers as wild pigs diffuse out of the less hunted areas.

#### RESULTS

The first step in running the model is to read in the map data. This includes the land usage and vegetation type and the position and type of the roads as well as the coastline. Fig. 4a shows the digitized version of the map data used by the model. The next step is to calculate the minimum time to get to each point in the province and thus the route taken to transport the pig to market. This is done by starting at the square con-

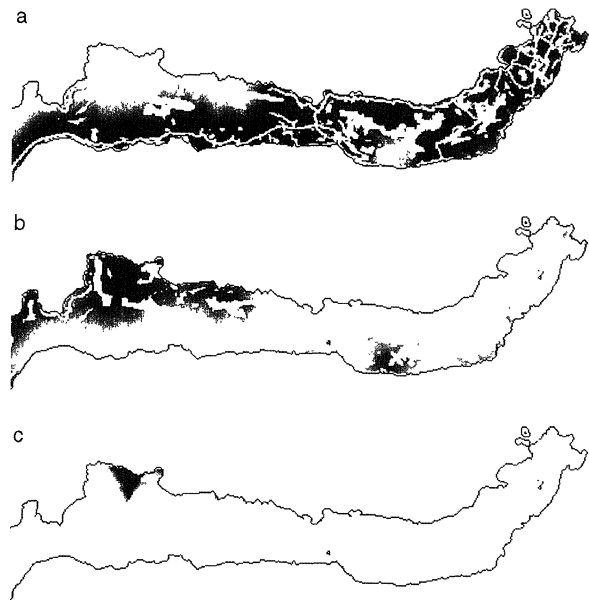


FIG. 5. Output of the model under 1995 parameter values (Table 1). In the figures, white represents a complete absence, and the sites are then scaled from light grey to black, black corresponding to  $H_{\min}$ ,  $K_w$ , and  $K_b$  in (a), (b), and (c), respectively. Maps show (a) the amount of harvesting at each site; (b) the number of Sulawesi wild pigs that can be supported at each site under this harvesting rate; and (c) the number of babirusas that can be supported at each site under this harvesting rate.

taining the provincial capital of Manado and forming a connected set of sites. This set keeps expanding so that at each step those of the remaining sites that can be reached fastest from Manado are added to it. Fig. 4b shows the times to reach each point; the scale goes from 0 to 96 h, which is the maximum time the meat can be stored. It can be seen from the figure that all points can be reached in 48 h under current road conditions.

Using the times and land-use types already calculated successive iterations of the scheme described above are performed on the harvesting levels at all points. Fig. 5 shows the level of harvesting, the number of Sulawesi wild pig, and the number of babirusa after 50 iterations, which is sufficient for convergence. The model predicts that under the current physical and economic circumstances the trapping of wild pigs will increase to such a rate that the babirusa will become extinct over the vast majority of the northern arm of Sulawesi (Fig. 5c). As can be seen from Fig. 3 only a relatively small amount of harvesting is necessary for the babirusa to be wiped out in any one area, whereas this amount of harvesting leaves the Sulawesi wild pig population virtually intact, causing a decline of <5%. In order to see whether the range contraction of the babirusa is an inevitable outcome of hunting or whether it is driven by the recent expansion of the road network, making it easier to reach all areas of the island quickly

TABLE 2. Parameter values for the model under 1950 road conditions (only those values that are different from the present-day values are included). Rp = Rupiah (US\$1 = Rp 2200).

Road type	Travel costs (Rp/km <sup>2</sup> )	Travel speeds (km <sup>2</sup> /h)
Primary road	270	15
Secondary road	332.5	10
Tertiary road	520	5

and easily, the program was rerun using the approximate road network from the 1950s; most of today's roads were in place then, but their condition was far worse, little better than dirt tracks. The parameter values used are shown in Table 2, and Fig. 4c shows the time taken to get to each point using these values. As can be seen from Fig. 4c, when the road network is less developed, the transportation times are greatly increased with it taking almost 4 d to reach some areas, the consequence of this being that in many regions the babirusa survive (Fig. 6). The areas in which the babirusa remain extant correspond fairly well to the regions where the population can be found today, thus supporting the results from the model if it is assumed that the real system is slow to equilibriate.

Under the assumption of a 1950s road network, the populations of Sulawesi wild pig and babirusa are 66 and 31% of their respective carrying capacities, whereas this has dropped to 37 and 4%, respectively, with today's roads. The results for the 1950s system could be made more precise if all of the prices were also altered; vehicles would have been proportionately more expensive then and hence the costs higher and the overall level of harvesting less. The forest cover was also more extensive then. A precise picture of the 1950s situation is not necessary, however, as this model has demonstrated that the improvement of the road system alone eventually leads to a dramatic drop in the population of both species of wild pig.

*Sensitivity analyses*

Sensitivity analyses were performed to show the effect of a 10% change in each parameter's value on the population sizes of the two species at equilibrium (Table 3a). The Sulawesi wild pig population is relatively robust to parameter changes, compared to the babirusa. The model is generally robust to parameter changes, including changes in the biological parameter values, such as catchability, carrying capacity, and intrinsic rate of reproduction, although it is sensitive to the catchability of the Sulawesi wild pig. This robustness allows us to have confidence in the model's results despite the lack of good data on the biological parameter values, although clearly the collection of catchability data should be a priority. The model is particularly sensitive to the hunters' walking speed in the forest and time taken to check snares, hunters' opportunity costs (wages), and wild pig prices. The walking

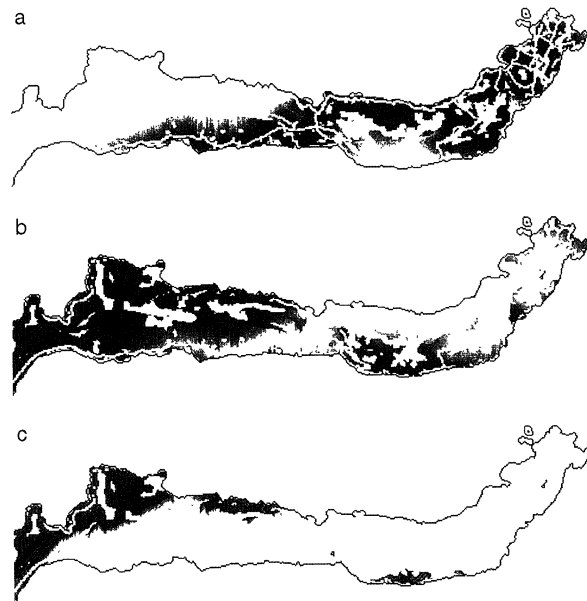


FIG. 6. Output of the model under 1950s parameter values (Table 2). In the figures, white represents a complete absence, and the sites are then scaled from light grey to black corresponding to  $H_{mm}$ ,  $K_w$ , and  $K_b$  in a, b, and c, respectively. Maps show (a) the amount of harvesting at each site; (b) the number of Sulawesi wild pigs that can be supported at each site under this harvesting rate; and (c) the number of babirusa that can be supported at each site under this harvesting rate.

speed and time taken to check the snares cannot be influenced by policy-makers wishing to conserve the babirusa, but they are related through time costs to the hunters' opportunity costs. These could potentially be influenced by policy-makers, as could the prices of wild pigs.

Two major assumptions of the model were also tested for their influence on the results (Table 3b). These were the assumption of interdependent harvesting of the two species and of the necessity to transport the meat to markets at the tip of the province rather than it being consumed locally. The results show how important these assumptions are for the outcome of the model, and thus the importance of including these features of the system into a realistic model. The single-species models are interesting in that if babirusa alone is hunted, without Sulawesi wild pig, it is not economically viable for hunting to occur, as the costs outweigh the profits from hunting. Thus the fact that babirusa is hunted along with Sulawesi wild pig is the reason why it is worth hunting it at all—a similar result to that found for rhinoceros and elephant hunting in the Luangwa Valley, Zambia (Milner-Gulland and Leader-Williams 1992). If, however, Sulawesi wild pig is hunted alone, without the babirusa, the increase in harvesting costs is small, leading to only a small increase in the Sulawesi wild pig population over its size under two-species harvesting. One of the most interesting features of this system is the effect of religious taboo on the hunting

TABLE 3. Sensitivity analyses. The numbers represent the percentage change in population size compared to the equilibrium under current parameter values (Table 1).

a) The effect of a 10% increase or decrease in the assumed value of each parameter on the equilibrium population sizes of the Sulawesi wild pig (SWP) and babirusa.

Parameter	10% increase		10% decrease	
	SWP	Babirusa	SWP	Babirusa
Primary road				
Cost	3.9	10.9	-4.0	-11.7
Speed	-1.6	-5.2	1.5	9.2
Secondary road				
Cost	1.0	10.8	-1.0	6.7
Speed	0.0	-3.0	0.0	5.0
Tertiary road				
Cost	0.7	2.2	-1.0	4.1
Speed	0.0	-1.4	0.0	-2.1
Walking speed				
Forest	-6.6	-37.3	6.5	54.0
Other	0.4	-8.2	0.4	11.3
Hunter's wages	16.4	73.7	-14.7	-42.8
Time to check snares	18.0	37.4	-14.5	-19.3
Price				
SWP	-20.0	-40.6	22.3	61.7
Babirusa	-0.3	-16.3	0.6	27.4
Catchability				
SWP	-14.7	-14.0	18.2	34.9
Babirusa	0.3	-3.0	0.0	-2.3
Carrying capacity				
SWP	8.5	-3.2	-8.0	8.2
Babirusa	-0.8	8.9	0.8	-1.9
Intrinsic rate of increase				
SWP	-1.3	-3.2	1.2	8.2
Babirusa	-0.8	-1.0	0.8	7.9

b) The effect of changes in the structural assumptions of the model. Note that if babirusa only are hunted, Sulawesi wild pig (SWP) populations increase to carrying capacity, and vice versa.

Parameter	SWP	Babirusa
Babirusa hunted alone	+183	+2580
SWP hunted alone	+15	+2580
Meat consumed locally	-65	-95

of wild pigs. In effect it is religious taboos that introduce the spatial element of the system through the need to transport wild pigs to market in the Christian tip of the province. It is clear from the sensitivity analyses that this imposes a substantial cost on the harvesters, allowing the equilibrium population of both species to remain much higher than it would be under the more usual circumstances of meat being hunted principally for local consumption.

#### DISCUSSION

The penalty for killing a babirusa is a maximum fine of Rp 100 000 000 (US\$45 454) or up to 5 yr in prison (Republik Indonesia 1990). In North Sulawesi province the average annual per capita income is Rp 720 766 (Kantor Statistik, Manado, 1993), so a fine of Rp 100 000 000 is an inconceivable amount of money to most citizens. The chances of being fined are minimal,

although dealers routinely incur the cost of giving pieces of meat to relevant officials. The law does not prevent the trapping and trade in babirusa because of a lack of awareness of wildlife laws and a lack of law enforcement. Detection of dealers carrying babirusa is not difficult, however, since all dealers must travel along the single road that links the western and eastern ends of the province. Checkpoints and road-tax payment points already exist along this road, but most dealers travel at night when these may not be manned. Detection of law breakers is also straightforward in the market since babirusa meat is displayed openly for sale and is distinguishable from Sulawesi wild pig meat.

The effectiveness of increased detection rates in reducing the numbers of babirusa carried by dealers was demonstrated during the field work component of this study. Annual special overnight checkpoints organized by the local authorities on the single road to the study

site were effective in preventing dealers from entering this one area to purchase meat between 1990 and 1994, whereas in September 1989 a single dealer had carried 17 babirusa from this site in 1 wk. Without the dealer entering to buy almost all trapping of wild pigs ceased in the area. Targeting the dealer, who is the sole supplier of string and purchaser of meat, is therefore an effective enforcement strategy. Effective deterrence has also been demonstrated in the end-market. Government officials were notified that babirusa were being sold in Langowan market, and as a result of this the numbers of babirusa sold openly declined from a mean of 34 babirusa/wk (February–April 1993) to 5 babirusa/wk (May–December 1993). However, law enforcement in the market was not sustained and the mean number of Babirusa sold per week rose again to 18 thereafter.

Law enforcement must be targetted to the prevention of babirusa hunting, as Sulawesi wild pig hunting is perfectly legal. The trapping method is nonselective, so both species will be trapped and killed if snares are set in the forest. However, if hunters set their traps in disturbed areas Sulawesi wild pigs are trapped but babirusa are not. Thus law enforcement tools that distinguish between the two species can differentially reduce hunting pressure on the endangered babirusa. Even if trapping remained nonselective, law enforcement on babirusa sale would still lead to increased populations of both species through an overall reduction in hunting pressure. This is because the reduction in the profit from selling babirusa would lead to there being less profit from hunting in an area and so to a decrease in the total hunting level, benefitting both wild pig populations.

From the sensitivity analysis (Table 3), three economic methods for the deterrence of babirusa hunting appear plausible. As all the dealers have to travel along a single road, the simplest to implement is probably a fixed toll on all vehicles carrying wild pigs (Fig. 7a). This has the advantage that it does not rely on distinguishing between Sulawesi wild pig and babirusa meat. However, as can be seen from the graph, tolls of over Rp 660 000 (US\$300) are necessary to bring the babirusa population back to the 1950s level of 31% of carrying capacity. This level of toll leads to a rise in Sulawesi wild pig population to over 85% of carrying capacity and so the total level of hunting has been dramatically, and probably unacceptably, reduced.

An alternative solution would be to impose fines in the market place for any dealer caught selling babirusa; this has the advantage that methods of trapping designed specifically to catch Sulawesi wild pig are unaffected. However this method would probably require more manpower as there are several markets that would require patrolling, and law enforcement officers would have to be trained to distinguish between the meat of the two species. Fig. 7b shows the size of the two wild pig populations against the size of expected fines. If the expected fine is above Rp 45 000 (the average price of a babirusa), then it is most profitable not to attempt

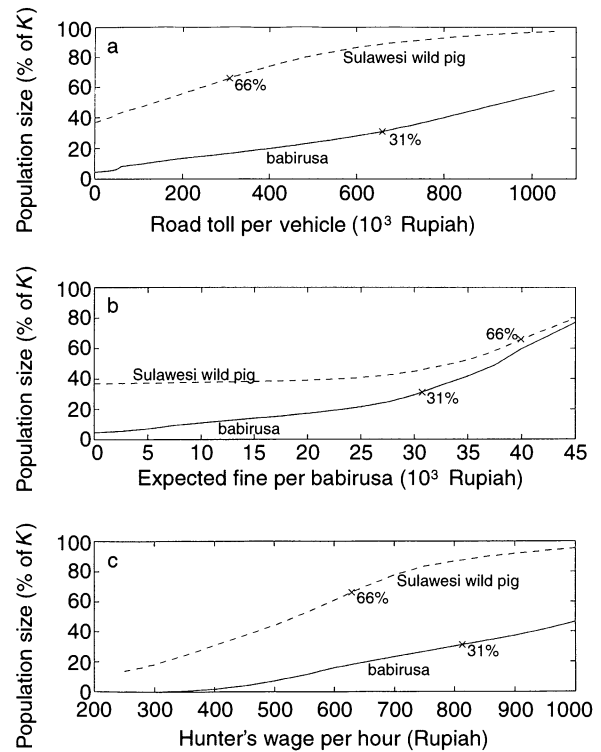


FIG. 7. The effects of law-enforcement measures on the Sulawesi wild pig and babirusa populations. The values of 66 and 31% of carrying capacity marked on the graphs represent the equilibrium population sizes of Sulawesi wild pig and babirusa, respectively, under the 1950s road network. Graphs show (a) vehicle tolls; (b) fines in the markets; and (c) changes in hunters' wage. The wage assumed in the model is Rp 450/h (US\$1 = Rp 2200).

to sell any babirusa. This method of fines leads to a significant increase in the babirusa population for a limited change in the Sulawesi wild pig population. Therefore it would appear that the total amount of hunting is affected little by this approach. This approach therefore appears both feasible and effective.

Note that Expected Fine is calculated as the size of the actual fine multiplied by the probability of incurring it. Thus, if there is a 50% chance of being caught and fined, the actual fine would be twice the expected fine shown here, assuming that the dealer is risk-neutral. As Leader-Williams and Milner-Gulland (1993) have discussed, the effectiveness of a given expected fine is actually much greater the higher the probability of detection (and so the lower the actual fine). This insight is due to studies of incentives to crime concentrating on theft and burglary in the USA, which concluded that penalty size is less of a deterrent than detection rate (Ehrlich 1973, Avio and Clark 1978), and that it is therefore a better strategy to concentrate on detection than on penalties. This result seems to transfer quite well to incentives to poach wildlife.

The final solution seems from the sensitivity analyses to be the most effective, i.e., a general increase in the

standard of living to raise the opportunity costs of hunting and hence the hunter's hourly wage (Fig. 7c). An increase in wages from Rp 450 to Rp 820 per hour is enough to return the babirusa population back to the 1950s level. However the converse is also true; if the hunter's wages decrease to below Rp 300/h that is sufficient to cause the extinction of the babirusa. Changes in opportunity costs rely, however, on changes in the economic health of the region as a whole, and therefore are virtually impossible for law enforcement officers to influence. An increase in standard of living could also have the effect of increasing consumer demand for wild pig meat, thus negating the effect of increasing opportunity costs.

The spatial model helps in the policy decision about the best means of law enforcement in various ways. The introduction of an explicit spatial element to the bio-economic model is the only way to obtain a true picture of the system, allowing the effects of the costs of hunting babirusa and Sulawesi wild pig to be correctly specified. Modelling the effects of changes in three economic parameters (a vehicle toll, market fines, and hunters' wages) allows policy recommendations to be made. It would appear that the introduction of fines for selling babirusa in the markets of Minahasa is the most advisable method of reversing the population decline as it has little effect on the overall level of hunting. Despite the pessimistic results for the future of babirusa in northern Sulawesi without intervention to conserve the species, the effect of altering hunters' wages shows that if the economic situation in the area improved the babirusa population might increase, as it would no longer be worthwhile for the hunters to walk as far in search of wild pigs.

The importance of the unusual features of this system for the outcome of hunting on population sizes and distributions is highlighted by the model. The fact that both species are hunted together, for the same end-market, means that the babirusa, the rarer species, is hunted to a level well below that at which it would be profitable to hunt it alone, while the commoner Sulawesi wild pig's population size is slightly increased by being hunted along with the babirusa. In fact, if it were not for the hunting of the Sulawesi wild pig, it would not be profitable to hunt babirusa at all given its current distribution. The concentration of wild pig meat consumers at the tip of Sulawesi is likely to lead to populations stabilizing at much higher levels than would have been the case if they had been spread throughout the island. The model also highlights the need to collect more basic ecological data on the two species, particularly on their distributions and catchability.

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