

Application of a Bioeconomic Production Model to Improve Wildlife Management

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ABSTRACT Faced with limited budgets, wildlife managers need to determine the set of management activities that achieve management objectives at least cost, which requires using both ecological and economic principles to make management decisions. We used data from a biological simulation model of breeding waterfowl to embed biological response within an economic optimization model. Nonlinearity of the response function was attributable to density dependence and interactions between jointly applied management activities. We then used the bioeconomic model to solve a waterfowl manager's least-cost problem. Model results demonstrated that 1) biological response and economic cost jointly determine the least-cost management plan, 2) nonlinearity of the biological response function should be modeled explicitly to identify cost-effective management plans, and 3) least-cost management plans depend on the chosen population objective. We demonstrate how concepts from production economics can aid decision making in a wide range of applied wildlife management settings; however, though applied to waterfowl management, we did not intend to provide a robust prescription for waterfowl managers. (JOURNAL OF WILDLIFE MANAGEMENT 72(2):510-517; 2008)

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Faced with limited budgets, wildlife managers need to determine the set of management activities that generate the desired outcome at least cost. To achieve cost-effectiveness, managers need 2 decision aids: 1) a biological model that predicts population response to various management activities (Hurley 1986), and 2) an economic model that relates management activities and the resulting population response to costs. Ecologists have expended considerable effort developing population response models, and economists have developed principles and models regarding the costs of production (e.g., Beattie and Taylor 1985, Verner et al. 1986). Unfortunately, whereas the need to integrate ecological and economic wildlife research has long been recognized (Pearse and Bowden 1968, Matulich and Adams 1987, O'Neill et al. 1998, Hughey et al. 2003), joint research efforts that produce practical insights for applied wildlife management remain scarce.

Many wildlife studies have considered costs (Lokemoen et al. 1982, Waer et al. 1997, Stephens et al. 1998, Nugent and Choquenot 2004); however, their focus is typically on response to one management activity, often applied at one level of intensity or scale (e.g., Zenner et al. 1992, Cowardin et al. 1998, Garrettson and Rohwer 2001). In practice, managers frequently apply multiple management activities simultaneously; therefore, they must also understand how productivity and costs change when activities are combined. In the absence of appropriate data, managers are required to assume management impacts are linear and additive (Lokemoen 1984, U.S. Fish and Wildlife Service [USFWS] 1996). These assumptions, however, may be inappropriate because many ecological relationships exhibit density dependence, implying

that response from incrementally increasing management will not increase linearly (Cowardin et al. 1995). Additionally, management activities applied simultaneously may interact to jointly determine response; thus, response from multiple management activities applied simultaneously is not the sum of response from each activity applied in isolation.

Bioeconomic models provide a conceptual framework for combining biological and economic functions to develop cost-effective management plans and to study how management recommendations change when wildlife response to management actions exhibit density dependence or when management activities are interdependent (Matulich and Hanson 1986, Cowardin et al. 1995, Rashford and Adams 2007). Use of economic concepts such as diminishing marginal productivity and activity interdependence to develop biological response leads to more realistic management plans. For example, Cowardin et al. (1995) showed that using average response measures (e.g., output/ha) scaled up to larger application levels can greatly overestimate management benefits. Cowardin et al. (1995:54) called for "more cooperative work with economists to give a sound economic basis for management decisions." Our analysis reflects such cooperation.

We used data on breeding mallards (*Anas platyrhynchos*) in conjunction with an economic optimization model to develop a static bioeconomic production model for identifying cost-effective management plans for mallards breeding in the Prairie Pothole Region of the United States, which includes land area in Minnesota, Iowa, North Dakota, South Dakota, and Montana. Our goal was not to provide detailed management prescriptions for waterfowl managers, but rather to use mallards to demonstrate how concepts from production economics can aid decision making across a wide

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Table 1. Area and percentage of total area in 9 land-use categories on the baseline landscape, characteristic of agricultural land in the Prairie Pothole Region, USA, used to simulate mallard response to management activities.

Land use	Area (ha)	% total area
Grain crops	560	69.3
Grassland	77	9.5
Hayland	54	6.7
Cropland retirement program	0	0
Seasonal wetland	60	7.4
Semipermanent wetland	40	4.9
Temporary wetland	4	0.5
Permanent wetland	1	0.1
Other	13	1.6

range of applied wildlife management settings. We extended the application of bioeconomic models to wildlife management by 1) examining properties of biological response across a large suite of management activities, which allowed for more complex response behavior; and 2) explicitly integrating biological response and economic optimization.

METHODS

Simulation and Regression: Estimating a Mallard Response Function

Given a lack of empirical data on mallard recruitment response across the range of management plans we wished to consider, we simulated the effect of land use and management actions on mallard recruitment using the Mallard Productivity Model (version 171.027beta; Cowardin et al. 1983, Johnson et al. 1987). The response variable was the number of recruits produced each breeding season. We performed simulations on a hypothetical 809-ha landscape that was characteristic of agricultural land in the Prairie Pothole Region (Table 1). We simulated mallard response to 8 management activities representative of those used for breeding waterfowl management: 1) cropland retirement (CR), 2) conservation tillage (CT), 3) delayed haying (DH), 4) planted cover (PC), 5) planted cover fenced (PCF), 6) artificial nest structures (NS), 7) predator control (PRED), and 8) restoration of semipermanent wetlands (WR). We simulated a range of possible management alternatives by varying the level of each management activity within the model (e.g., 100–800 ha of CR), first in isolation, then in combination with other activities, to capture substitution possibilities and interdependence between activities. In total, we simulated 376 combinations of management activities (i.e., management plans).

We made several simplifying assumptions to reduce the number of simulations required to capture important properties of response functions and simplify collection of cost data. First, we assumed CR, CT, and WR replaced grain crops (i.e., to simulate 100 ha of CR, we input 100 ha of CR in the Mallard Productivity Model in place of 100 ha of grain crops). Second, we assumed DH, PC, and PCF replaced hayland and grassland. Third, we limited density of NS to one structure per 0.4 ha of wetlands to be consistent with densities observed in the literature (Bishop and Barrat 1970, Marcy 1986). Last, we assumed PRED was a discrete

variable (i.e., predator control must be applied to the entire landscape or not applied at all) to be consistent with ecological studies that indicated predator redistribution and dispersal limited the effectiveness of lethal control on small habitat patches (Garrettson and Rohwer 2001).

The Mallard Productivity Model is stochastic; therefore, our estimate of recruitment for each management plan was the mean of 300 model runs. We chose 300 simulation runs by iteratively simulating response and calculating a 95% confidence interval around the estimated mean at each iteration (Ross 2002). At 300 simulations, the confidence interval around the estimated mean converged with a 95% confidence interval of ± 1.5 recruits.

Our simulations generated a set of recruitment point estimates corresponding to each simulated management plan ($n = 376$). We used this data set to statistically test density dependence and interdependence between management actions to determine relevant response relationships as predicted by the Mallard Productivity Model. Traditionally, tests of density dependence hold area fixed and vary population size. In our model, pair abundance was relatively constant, but density of nests on the landscape varied as abundance of suitable nesting habitat changed. For example, predator research indicated that large blocks of intact dense nesting cover reduced nest density and decreased the probability that predators located and depredated nests (Sovada et al. 2000). Although it was possible to estimate second-order terms (density dependence) and interaction terms (interdependence) for every management activity directly using the Mallard Productivity Model data, this was not advisable because of potential for inefficient parameter estimates (Greene 2000). We therefore consulted the literature and management professionals to identify, a priori, combinations of management activities predicted to exhibit density dependence and interdependence. Previous research suggested management activities that directly increased mallard nesting habitat would exhibit density dependence because, given a relatively fixed number of breeding pairs in an area, recruitment will increase at a decreasing rate as quantity of nesting habitat exceeds breeding pairs' needs (Cowardin et al. 1995). We therefore included second-order (quadratic) terms for CR, DH, CT, PC, PCF, and NS.

We next identified management activities believed to exhibit competitive or complementary interdependence. We expected habitats similar in their attractiveness to breeding waterfowl to compete for the limited number of breeding pairs; therefore, CR, PC, and PCF may be competitive. We expected predator control to compete with activities that created extensive nesting cover (i.e., influence nest density) and we therefore included interaction terms between PRED and CR, CT, DH, and PC. Lastly, wetland abundance affects number of breeding pairs on a landscape; therefore, we predicted wetland restoration would complement other activities by increasing number of breeding pairs available to use them. We therefore included interaction terms between wetland restoration and all other activities.

Table 2. Annualized mallard management activity costs per unit (based on waterfowl management expenditures in the Prairie Pothole Region, USA) expressed in real United States dollars deflated to the base year 2004.

Management activity	Cost (\$)
Predator control	4.94
Nesting structures	22.90
Conservation tillage	37.07
Planted cover	43.24
Delayed hay	61.78
Cropland retirement	81.54
Wetland restoration	93.90
Planted cover fenced	272.31

We used multivariate least squares regression (Limdep NLOGIT 3.0; Greene 2003) and a second-order quadratic equation to estimate the mallard response function relationship. The estimable equation had the form:

$$y = \alpha + \sum_i^k (\beta_{1i}x_i + \beta_{2i}x_i^2) + \sum_i^k \sum_{j \neq i}^k \delta_{ij}x_ix_j + \varepsilon, \quad (1)$$

where y is the mean number of recruits, x_i is the level of management activity i , ε is a normally distributed random disturbance term, which captures unobserved determinants of recruits, and α , β_{1i} , β_{2i} , and δ_{ij} are response coefficients to be estimated. The unit of measurement for all activities was hectares, except for NS, which we measured as number of nesting structures installed. Parameters β_{2i} and δ_{ij} captured density dependence and activity interdependence, respectively. Specifically, management activity i exhibited density dependence if $\beta_{2i} < 0$. Management activities i and j were independent, complementary or competitive if $\delta_{ij} = 0$, $\delta_{ij} > 0$, or $\delta_{ij} < 0$, respectively. To test robustness of the model, we tested if β s or δ s differed from zero using t -tests.

Following statistical tests of the biological variables, a final form of the regression model was specified, as a continuous function, to predict recruitment response for any possible management plan. We included the linear (independent) form of any variable that did not show density dependence or interact with other variables. This final equation served as the biological component of our economic optimization model (see below) used to determine cost-effective management plans.

Optimization: Estimating Mallard Management Cost Functions

We embedded the estimated mallard response function within an economic optimization model to determine least-cost mallard management plans. We used the optimization procedure to compare least-cost management plans developed assuming linear and nonlinear response to determine the effect of response characteristics on management cost-effectiveness. The economic model required estimates of management costs (Table 2), which we collected from management literature and through correspondence with waterfowl managers. Activity costs included land-use cost, which included the opportunity cost of foregoing or altering agricultural production (e.g., foregone returns from delaying hay harvest), management costs, and construction costs

when applicable (see Rashford 2006). We annualized appropriate costs to make management activities with different useful life spans comparable on an annual basis. Thus, these costs represented what a manager would need to spend annually per unit to apply the management activity.

The economic optimization model had the following form:

$$\min_{x \geq 0} \sum_{i=1}^n w_i x_i, \quad (2)$$

subject to

$$\hat{\alpha} + \sum_i^k (\hat{\beta}_{1i}x_i + \hat{\beta}_{2i}x_i^2) + \sum_i^k \sum_{j \neq i}^k \hat{\delta}_{ij}x_ix_j \geq y^* \quad (3)$$

$$\sum_i x_i \leq A_{\text{grain}}, i = \text{CR, CT, WR} \quad (4)$$

$$\sum_i x_i \leq A_{\text{hay}} + A_{\text{grass}}, i = \text{DH, PC, PCF} \quad (5)$$

$$x_i \leq 0.4(x_j + A_{\text{wetland}}), i = \text{NS}, j = \text{WR} \quad (6)$$

$$x_{\text{PRED}} = \{809 \text{ if PRED is initiated, } 0 \text{ otherwise}\} \quad (7)$$

$$0 \leq x_i \leq X_i, \forall i \neq \text{PRED}. \quad (8)$$

Hats (^) indicate coefficient values estimated in the regression model; x_i was the level of management activity i (e.g., ha); w_i was the annualized per unit cost of activity i ; A_{grain} was the initial hectares in grain crops on the landscape; A_{hay} was the initial hectares of hayland on the landscape; A_{grass} was the initial hectares of grassland on the landscape; A_{wetland} was the initial hectares of wetlands on the landscape; and X_i was the maximum amount of activity i that can be applied given initial landscape characteristics. The first constraint (eq 3) established the production objective by requiring that the number of recruits produced was greater than an exogenously chosen target level (y^*). Constraints 4 and 5 captured land-use constraints and were included to ensure the optimization model was consistent with simulated data. Equation 4 limited CR, CT, and WR to no more than the initial eligible hectares. Equation 5 limited DH, PC, and PCF to no more than the initial eligible hectares. Equation 6 constrained NS to <0.4 structures per hectare of total wetlands. Constraint 7 established PRED as a discrete variable, and constraint 8 established the range for all other variables.

In problem 2, $\sum_{i=1}^n w_i x_i$ was the management expenditure associated with a given combination of management activities. The solution to problem 2 was the cost-effective management plan (x_1^*, \dots, x_n^*) that achieves y^* at least total cost ($\sum_{i=1}^n w_i x_i^*$). We solved the cost-minimization problem for every possible recruit target (y^*) from 0 to y^{max} (max. no. of recruits that can be produced given land-use constraints) to derive total cost, marginal cost, and average cost functions.

Table 3. Least squares regression estimates for mallard response as a function of 8 management activities (linear [PC], quadratic [PC²], and interaction terms [PC × PRED]). Response data simulated with the Mallard Productivity Model; $n = 376$.

Management activity ^a	Estimate	SE ^b
Intercept	17.82	1.56
NS	3.69	0.227
PCF	1.10	0.059
WR	0.34	0.04
DH	0.31	0.062
PC	0.20	0.032
PRED	0.16	0.002
CR	0.04	0.007
CT	0.03	0.007
NS ²	-0.0463	0.006
PCF ²	-0.0043	0.0004
PC ²	-0.0004	0.0001
PRED × DH	-0.0012	0.0002
CR × PCF	-0.0012	0.0002
PRED × PC	-0.0004	0.00006
PRED × CT	-0.0002	0.00006
PRED × CR	-0.0001	0.00001
CR × PC	-0.00003	0.0001

^a CR = cropland retirement program, CT = conservation tillage, DH = delayed hay, NS = nest structures, PC = planted cover, PCF = planted cover fenced, PRED = predator control, WR = wetland restoration.

^b All $P < 0.01$, except CR × PC.

The total cost function, $C(w,y)$ reported minimum total cost of achieving any possible recruit target. From $C(w,y)$ we derived the marginal cost (MC) function ($MC = \frac{\partial C(w,y)}{\partial y}$) and average cost (AC) function ($AC = \frac{C(w,y)}{y}$). The MC function described change in the cost function given a small change in recruit target y . The AC function described, for every point on $C(w,y)$, cost per recruit. Last, we solved the cost-minimization problem assuming all mallard biological responses to management activities were linear (i.e., all second-order and interaction terms in eq 3 were set to zero) to demonstrate consequences of such a simplifying assumptions regarding biological response.

Finally, to illustrate the interplay between productivity and cost in determining cost-effective strategies, we constructed an isoquant–isocost map for one pair of management activities: planted cover fenced and conservation tillage. Isoquant lines show all combinations of 2 activities that can produce the same number of recruits. Similarly, isocost lines show combinations of 2 activities that can be implemented for the same total cost. Cost-effective combinations of the 2 activities correspond to tangencies (interior or corner) between the isoquant for the targeted recruit level and the lowest isocost level attainable.

RESULTS

Simulation and Regression: Mallard Response Function

Regression with the full variable set indicated that mallard productivity did not vary with CR², DH², CT², and PC × PRED and all interaction effects involving WR ($P > 0.01$). We removed all insignificant second-order and interaction terms (retaining linear forms) and reestimated the response function for use in our economic model. The final specification fit the data well ($F_{376,18} = 304.8$, $R^2 = 0.935$,

and adjusted $R^2 = 0.932$). Artificial nest structures had the largest effect on recruitment, followed by PCF, WR, DH, PC, PRED, CR, and CT (Table 3). Thus, the first NS produced more mallard recruits than the first unit of any other management activity (the first NS was >3 times as productive as the first unit of PCF). Effect of CR, DH, CT, and PRED on recruitment was linear (P -value for all quadratic terms > 0.01), whereas NS, PC, and PCF showed density-dependent responses (Table 3). Most interaction terms were not significant, indicating most management actions could be viewed independently from others. However, CR interacted with PC and PCF, and PRED interacted with CR, DH, CT, and PC (Table 3). All significant interactions were negative, indicating activities were competitive. Thus, for example, at the maximum application level of PRED (809 ha) and CR (560 ha) on the simulated landscape, a model that omitted the competitive interaction between these activities would overestimate production by 30%.

Optimization: Mallard Management Cost Functions

The baseline landscape with no management activities produced an average of 18 recruits, as indicated by the intercept term, and application of the 8 management strategies on our virtual landscape produced a maximum of 277 recruits (determined by maximizing eq 3 subject to constraints 4–8). The cost functions behaved as predicted (Fig. 1); marginal costs increased at an increasing rate, due to diminishing marginal productivity of many management activities (Fig. 1B). The first recruit produced using only NS had a marginal cost of \$6.23, whereas the marginal cost of the last recruit (277th), produced with a combination of NS, WR, PCF, and PRED (Fig. 1B), was \$819.

Results indicated that biological response and cost jointly determined cost-effectiveness. The order that activities first appeared in cost-effective plans (NS, WR, DH, PRED, and PCF) did not match the variables when ranked by relative biological productivity (NS, PCF, WR, DH, PC, PRED, CR, and CT) or by relative cost (PRED, NS, CT, PC, DH, CR, WR, and PCF). Three activities (CR, CT, and PC) were never cost-effective at any target recruit level. The isoquant–isocost map further demonstrated the interplay between biological response and cost in determining cost-effectiveness. For example, the isoquant–isocost map indicated that 10 recruits could be produced with 400 ha of conservation tillage for a total cost of \$14,828 (Fig. 2, point A). However, because PCF was more productive; the target of 10 recruits could be produced with 9.4 ha of PCF for a total cost of \$2,550 (Fig. 2, point B). Thus, despite PCF being >7 times as costly per hectare as CT, it could be cost-effective to implement PCF instead of CT.

The cost-minimization model assuming linear response resulted in cost-effective management plans that differed from the nonlinear model. At low recruit targets, the linear model applies fewer NS than the nonlinear model. For example, to produce 68 recruits the linear model applied 29 NS, whereas the nonlinear model applied 35 NS. As a result, cost functions between the 2 models also differed

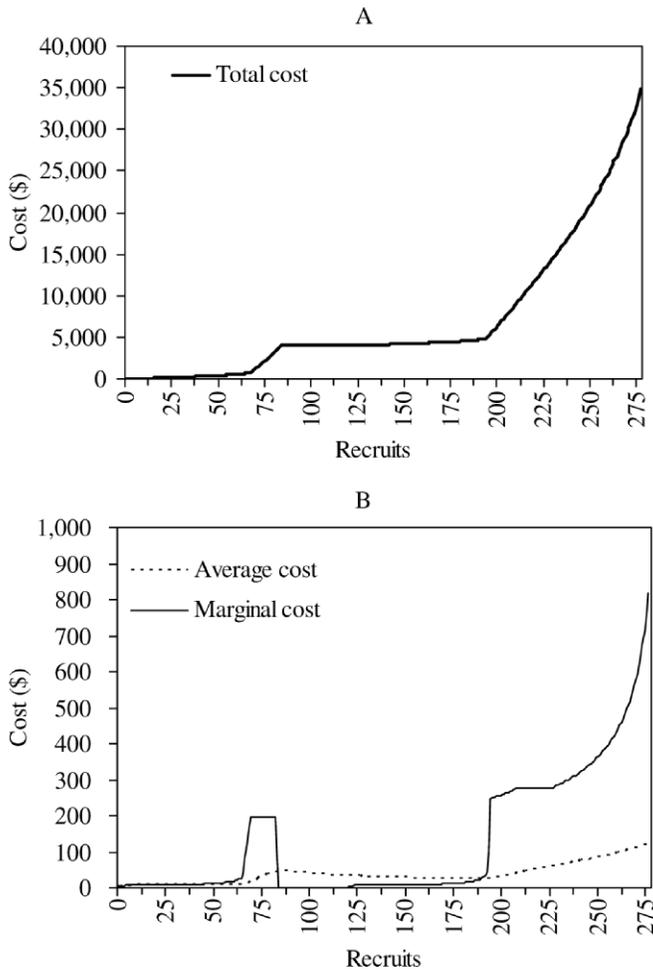


Figure 1. (A) Total cost function indicating the total expenditure necessary to produce 0–277 mallard recruits, and (B) average cost function and marginal cost function indicating the cost per recruit and incremental cost of each recruit level, respectively. We estimated cost functions by minimizing the total cost of management subject to achieving a specific recruit target using mallard response data simulated with the Mallard Productivity Model and cost data consistent with waterfowl management expenditures in the Prairie Pothole Region, USA. Costs are expressed in United States dollars deflated to the base year 2004.

(Fig. 3). Over the recruit target range where only NS were applied in the cost-effective solution, the linear model results in a constant $AC = MC$ of \$6.21, whereas MC and AC in the nonlinear model increased at an increasing rate. As the recruit target approached the limits of available management resources on the landscape, the linear and nonlinear models converged (not shown).

The cost-effective mix of management activities also varied with the recruit target (Fig. 4). There were 244 different cost-effective management plans (each specifying type and intensity of various management actions) depending on the recruit target. At low recruit targets (up to 65 recruits), it was only cost-effective to increasingly apply nest structures. Predator control was cost-effective at targets >84 recruits, PCF at >195. At 250 recruits, the most cost-effective plan included 40 NS, 50 ha of WR, 30 ha of PCF, and 800 ha of PRED. Thus, the cost-effective management

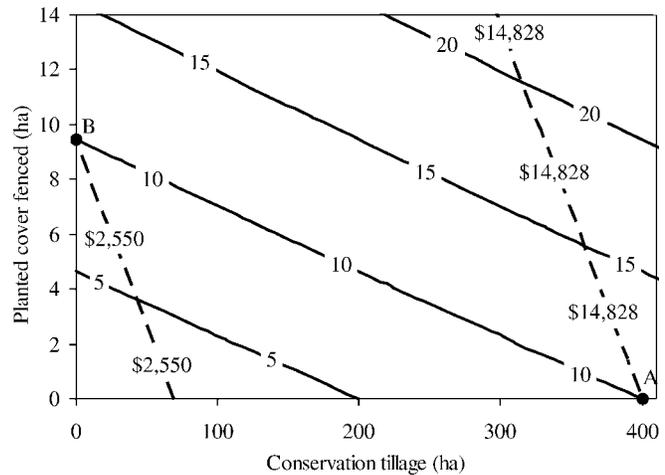


Figure 2. Mallard production isoquants (solid lines) and isocost lines (dashed lines) for planted cover fenced (PCF) and conservation tillage (CT) management activities, consistent with waterfowl management expenditures in the Prairie Pothole Region, USA. Isoquants show all combinations of PCF and CT that produce the same level of recruits; isoquant labels indicate number of recruits produced. Isocost lines show all combinations of PCF and CT that can be employed for the same level of total cost; isocost labels indicate total cost level. Costs are measured in United States dollars deflated to the base year 2004. Point A indicates that 10 recruits can be produced with 400 ha of CT and 0 ha of PCF, for a total cost of \$14,828. Alternatively, point B indicates that 10 recruits can be produced with 9.4 ha of PCF and 0 ha of CT, for a total cost of \$2,550.

plan was highly variable depending on management objectives. For some recruit levels, it was optimal to apply only one activity. For other recruit levels, it was optimal to combine multiple activities at varying levels; however, it was never optimal to combine activities that were competitive.

DISCUSSION

Simulation and Regression: Mallard Response Function

Our final model of biological response differed from several of our predictions. Many activities we expected to exhibit density dependence or to be competitive (e.g., PC and PCF) and complementary (e.g., WR and all other activities) were not. In part, disagreements with predictions and between our analysis and a previous analysis (Cowardin et al. 1995 found CR was density dependent) may reflect the influence of geographic scale on results. Our simulated landscape was smaller than that of Cowardin et al. (1995; 809 ha vs. 5,180 ha). Our smaller model landscape may have constrained the size of the biological response making it more difficult to detect second-order effects. Such differences indicated more multiple-scale field studies (e.g., Stephens 2003) are needed to determine how scale impacts response functions so managers can make more informed decisions regarding cost-effective management. Additionally, the Mallard Productivity Model was not spatially explicit; therefore, wetland locations within the management area and presence of wetlands on neighboring landscapes did not influence response. Spatially explicit models may be better suited for identifying the complementary relationships between wetland restoration and other activities (Guyn et al. 2006).

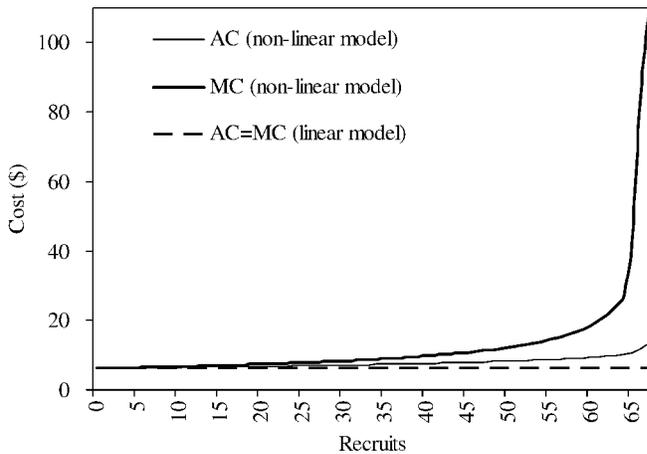


Figure 3. Marginal cost (MC) and average cost (AC) functions for mallard production over the range of 1–68 recruits assuming linear (dashed line) and nonlinear (solid line) mallard response to management. Functions were derived by minimizing the total cost of achieving each recruit level using mallard response functions estimated from data simulated with the Mallard Productivity Model and management cost estimates consistent with waterfowl management expenditures in the Prairie Pothole Region, USA (costs expressed in United States dollars deflated to the base year 2004).

Optimization: Mallard Management Cost Functions

The integrated bioeconomic model indicated ecological response and economic costs jointly determined cost-effective management plans. The mallard response function, for example, indicated PCF was a highly productive management activity; however, PCF was not implemented in the cost-effective solution until the production target exceeded 194 recruits (70% of total production possible) due to its relatively high per-unit cost. Conversely, CT was one of the least expensive activities examined, but CT never appears in a cost-effective solution because of its relatively low marginal productivity. Thus, management activities should not be quickly adopted simply because biological experiments indicated that they were highly productive, nor should activities be quickly dismissed because of high per-unit costs. Interplay between productivity and response determined cost-effectiveness.

The functional nature of response (e.g., linear vs. nonlinear) also had a large impact on identification of cost-effective management plans. Because mallard response was nonlinear for several management activities, marginal cost and average cost of production were not constant across activity levels. Our results followed those of Cowardin et al. (1995), who warned that expressing management results as recruits per hectare then scaling up by multiplying recruits per hectare by the number of hectares to be managed may greatly overestimate the number of recruits produced. To this, we add that overestimating production from management activities will lead to underestimating the cost of achieving a given production level and, therefore, lead to cost-inefficient applications of management. For example, in the absence of diminishing marginal productivity $AC = MC$ and the linear model resulted in a constant AC of \$6.21 for the first 68 recruits produced. In contrast, when we modeled density dependence, MC increased at an increasing

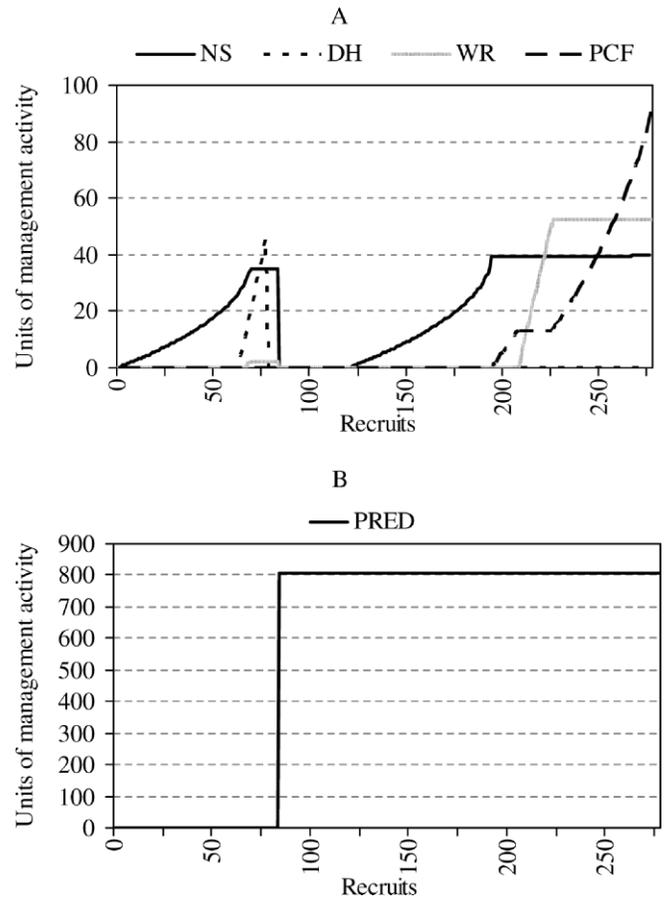


Figure 4. Least-cost combinations of 8 mallard management activities to achieve a range of recruit targets (0–277). Note that the figure should be interpreted vertically such that for a given recruit target on the horizontal axis, the cost minimizing activity levels for (A) NS, DH, PCF, and WR, and (B) PRED are given by the vertical intersection with the respective activity level line. NS = artificial nest structures (no.), DH = delayed hay (ha), WR = wetland restoration (ha), PCF = planted cover fenced (ha), PRED = predator control (ha).

rate (i.e., each additional nest structure produces fewer recruits than the last), and therefore, each additional recruit costs incrementally more to produce. When diminishing marginal productivity was considered, producing 68 recruits actually required 34 nest structures with an AC of \$13.26 and MC of the 68th recruit was \$108.

Studies of individual management activities that assumed a linear response (i.e., $MC = AC$; see e.g., Lokemoen 1984, USFWS 1996) imply that observed production levels can be scaled up or down, and the AC and MC of that changed production level will remain the same. If in reality the response is nonlinear (e.g., scaling was done around a point of large diminishing marginal productivity), then the assumption of constant AC and MC may severely underestimate true costs of production. In a nonlinear world, both AC and MC will vary with productivity changes, but AC will change more slowly, because when MC increases rapidly, AC only increases slightly, as it averages the high cost of the last recruit produced over all the recruits produced to that point. Thus, AC alone is an incomplete measure of cost-effectiveness because it does not indicate the

true cost of producing the marginal recruit. The MC is the appropriate measure of the incremental cost of production, which was illustrated in the above example where it may be easy to justify spending \$13.26, on average, to produce 68 recruits, though it would be more difficult to justify spending \$108 to produce the 68th recruit, as was the case.

Our analysis also indicated the cost-effective management plan varied depending on target production level. Activities that were cost-effective for low levels of production may not be cost-effective for high levels of production, which was particularly true for those management activities that were discrete, such as PRED. The discrete, all-or-nothing nature of PRED caused a corresponding discrete change in the cost-effective management plan. Management objectives must, therefore, be clearly identified to design cost-effective management plans. Somewhat surprisingly, our analyses indicated that several commonly used management practices were never cost-effective to implement, regardless of the recruit target. Many activities, however, produced benefits beyond waterfowl production (e.g., reduced erosion from CR, songbird habitat from PC) and may be justified on these grounds. Additionally, management agencies must consider a broad array of sociopolitical preferences (e.g., pressure from anti-predator control organizations), and the incentives these preferences create may override biological and economic considerations.

Finally, our analysis had several limitations that should be considered for future research. We demonstrated production economic concepts using a discrete landscape scale and one species. More field experiments are needed to explore how cost-effectiveness of management plans change as scale is adjusted. Furthermore, at larger scales management costs will likely vary across alternative landscapes depending on land quality. Heterogeneous land costs further complicate the decision problem and can have substantial effects on cost-effective targeting of management dollars (Rashford and Adams 2007). Such a future analysis could be informative for managers attempting to transfer successful management plans between management areas of differing scales or to choose which management areas warrant the largest investments. Additionally, our modeling approach could be expanded to include multiple species; however, interdependence between management activities is likely to be increasingly complex in this setting. The need for more complex models to deal with increasingly complex questions will require continued cooperation between wildlife managers and economists. Last, our approach only considered waterfowl supply. Demand for waterfowl, in the form of hunting and nonconsumptive viewing, would need to be integrated into management decisions to identify optimal regional population levels and guide state and/or national policy-making (see Hammack and Brown 1974 for an early attempt at such an analysis).

MANAGEMENT IMPLICATIONS

The cost-effective management plan varied with the desired production level (i.e., no. of recruits); thus, policy-relevant

applications of bioeconomic production models require that production targets (e.g., in this case no. of recruits) be explicitly stated. Managers rarely target a given production level, in part, due to the difficulty of measuring output in the field. Nonetheless, broad objectives, such as increasing the population, are not specific enough to account for incremental costs associated with increasing populations, nor the discrete nature in which cost-effective strategies could change. It may be more effective, for example, to target lower but more cost-effective production levels and use cost savings in other management areas or to pursue other objectives. Insights from production economics also suggest that managers should consider the full range of affordable management plans, a priori, instead of implementing individual management activities incrementally, which may lead to redundant management practices. Although applying this recommendation in practice may be difficult, because the marginal cost of wildlife production is rarely known, simply considering management plans as a suite of activities that are interrelated instead of a collection of individual activities can move managers in the direction of increased cost-effectiveness. It remains for economists and biologists to develop a user-friendly modeling tool that can be used to assist managers in this regard.

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