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A theoretical basis for study and management of trampling by cattle

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Abstract

Cattle trampling of endangered plants, certain animal species, and ground nests may be a management concern on rangeland. Researchers need theoretical models of trampling loss to assist in design of studies and interpretation of results. Managers can use such models to assist in grazing management decisions. We present null (random background) models for predicting probability of trampling loss, explore the effects of failure of assumptions underlying these models, and develop alternative models for dealing with nonrandom grazing and nonrandom placement of vulnerable objects. The null models predict that if time-based stocking rate (head-days ha^{-1}) is held constant and 1 pasture is grazed under several rotation schedules (a study design used to simulate rotational grazing), or if 1 pasture is divided into *n* paddocks through which 1 herd rotates, the probability of trampling is operationally constant. This qualitative prediction holds when grazing is nonindependent and nonrandom, competing risks exist, and objects subject to trampling are dispersed nonrandomly. Quantitative predictions of the null models do not hold under nonrandom grazing, which is expected to reduce probability of trampling. Researchers can use predictions of the models as *a priori* hypotheses. If empirical results deviate from the predictions, then researchers should search for the underlying cause-effect mechanisms. For management, the models indicate that trampling varies with livestock density and time grazed but is independent of herd rotation.

Key Words: continuous grazing, grazing, probability, short duration grazing, trampling.

Livestock trampling of endangered plants (Schemske et al. 1994), sensitive animals species such as desert tortoises (*Gopherus agassizi*) (Berry 1978), and nests of ground-nesting birds (Bryant et al. 1982) has become a management concern on rangeland. The concern intensified as grazing technology evolved from simple continuous grazing (1 herd in 1 pasture) to short duration grazing (1 herd rapidly rotated through several paddocks in 1 pasture) (Bryant et al. 1982). Per-paddock, short-term (3 to 7-day) stocking rates under short duration grazing may be up to 90 times that of a continuously grazed pasture (Savory and Parsons 1980), which would increase trampling. However, unlike continuous grazing, a high percentage of a pasture under short duration grazing is devoid of livestock at any time.

Concern about trampling loss prompted several studies of nest trampling (Bryant et al. 1982, Koerth et al. 1983, Bareiss et al. 1986, Beintema and Muskens 1987, Jensen et al. 1990). These empirical data were collected under different experimental designs and stocking rates. Some data were based on nests subject to predation whereas others were not (clay targets served as simulated nests). No attempt has been made to synthesize these empirical results into a general theory of trampling, nor to develop the probabilistic basis of trampling loss.

We develop probabilistic models of trampling loss, which we call null models because they hold under assumptions of random conditions. These models provide expectations in a random environment, and deviations from these expectations, if observed in the field, highlight the need to search for cause-effect processes. We explore the robustness of the models to assumption failure, e.g., nonrandom grazing, and develop alternative models for dealing with assumption failure. We test predictions of the null models against published data on trampling loss and show that the models are consistent with published results. Finally, we derive the probability of trampling for 1 head (cattle) grazing 1 ha for 1 day based on data from Jensen et al. (1990). The latter variable can be used as a basis for evaluating trampling loss rates under different grazing management strategies, which we illustrate with example applications and calculations.

Random Background and Null Models

The concepts we present are based on cattle. However, the models could apply to any class of livestock or wild ungulate under appropriate corrections for base probability of trampling (defined below).

We first develop assumptions underlying the null models. These assumptions may fail or hold approximately in the field; we address the implications of assumption failure in the next section. The known assumptions are as follows: all objects in a pasture are vulnerable to trampling for a complete grazing period of interest, vulnerable objects are dispersed randomly within pastures, each animal grazes randomly and independently of all other animals in a pasture, the grazing patterns are independent among days, and trampling is the sole source of loss of objects. We also impose the condition that reference time periods are reasonable relative to trampling loss rates. This condition is required because

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trampling probabilities start at zero and converge to one as time passes.

Under the above assumptions and conditions, consider a situation where 1 head of cattle grazes a 1-ha pasture for 1 day, which generates what we define as the base probability of trampling. Let the base probability of trampling be q and the probability of survival be $p = 1 - q$. With h head of cattle grazing t days, probability of loss is estimated as

$$P(\text{loss } h|\text{head, 1 ha, } t \text{ days}) = 1 - (1 - q)^{ht}. \quad (1)$$

Simulated Rotation in Field Studies

For reasons of economics and replication in field studies, it might be useful to simulate full-scale rotational grazing at a small scale. We might, for example, have a study design with three 1-ha pastures subjected to 3 treatments: 1 grazed at 1 head for 8 days, 1 grazed at 2 head for 4 days and rested 4 days, and 1 grazed at 8 head for 1 day and rested 7 days. In each of these treatments the time-based stocking rate, i.e., the product of number of livestock times number of days of grazing, is constant at 8 head-days ha^{-1}.

In the simplest case with 1 ha, we could have 1 head grazing for 2 days or 2 head grazing for 1 day, each of which yields a time-based stocking rate of 2 head-days ha^{-1}. In either case, the probability of loss is identical under Equation (1), because the exponent of $(1 - q)$, i.e., ht, is constant. Therefore, Equation (1) leads to the following qualitative prediction: notwithstanding sampling variation, field studies that simulate rotation grazing as specified should find differences in trampling rates only if time or stock density is manipulated such that time-based stocking rate varies among treatments; otherwise, the expectation is similar trampling loss rates.

Full Scale Rotation in Field Studies

Results from a study with the above design lead to the conclusion that rotational and continuous grazing have the same effects on trampling loss rates, given a constant time-based stocking rate and the specified assumptions. To test this prediction in a field-scale setting, we need to generalize the variable $q = P(\text{loss}|1 \text{ head, 1 ha, 1 day})$ to areas of any size. This can be accomplished by defining

$$P(\text{loss}|1 \text{ head, } A \text{ ha, 1 day}) = qA^{-1},$$

which implies that the probability of trampling for 1 animal varies inversely with the area over which trampling is applied. We now develop a null model for probability of loss as a function of n paddocks ($n \geq 1$) on A ha. If $n = 1$, we have continuous grazing. Define T = the number of days to complete 1 rotation of the herd through the paddocks. Let each paddock be of constant size (A/n) and let each be grazed for a constant number of days (T/n). With h head of cattle, we can specify the loss on each paddock as

$$P(\text{loss}|h, A, T, n) = 1 - (1 - qn/A)^{hT/n} \quad (2)$$

The loss on each paddock represents $1/n$ of losses on the entire pasture during 1 full rotation of the herd. Because the losses on each paddock are additive over n paddocks, Equation (2) describes pasture-wide loss on the area A as well as paddock-specific loss.

The mathematical expectation from Equation (2) is for probability of trampling loss to increase as the number of paddocks increases, holding other variables constant. However, the increase is operationally trivial under realistic field conditions. The qualitative prediction specified above remains acceptable.

It follows from Equation (2) that if the stocking rate is increased under short duration grazing, which is the economic rationale for costs associated with increased fencing and management intensity, then expected trampling loss increases. Whether the increase is consequential from a management standpoint depends on numerous social, economic, and biological factors that must be evaluated on a case-by-case basis.

Assumption Failure and Alternative Models

In this section we explore robustness of the null models (Equations [1] and [2] to assumption failure, describe the quantitative implications of assumption failure, and provide models that are applicable when one or two assumptions are not viable. Readers must recognize that when we address breakdown of any one assumption, other assumptions remain in force. Hereafter we drop the conditional probability notation for convenience.

Partial Exposure in Time

Objects such as ground nests might not be exposed to trampling for an entire grazing period, which should reduce the probability of trampling. In the reasoning that follows, we arbitrarily set the period of exposure to trampling (v) at some value less than the grazing period of interest (T).

If a ground nest requires v days to lay and incubate, then under continuous grazing it is exposed to trampling for v days. The probability of loss becomes

$$P(\text{loss}) = 1 - (1 - q/A)^{hv} \quad (3)$$

The relationship is more complex under short duration grazing. A nest may be started on any paddock at any time. Therefore, it may be exposed to trampling on different paddocks for different periods of time in v days. Further, under the constraint given above ($v < T$), the probability of loss is conditional on nest placement in a grazed paddock. To simplify presentation, we impose the conditions that a nest starts when cattle enter a paddock and that v is an integer multiple of days grazing per paddock (T/n). Under these conditions and constraints for short duration grazing ($n > 1$),

$$P(\text{loss}) = (v/T)[1 - (1 - qn/A)^{hT/n}]. \quad (4)$$

Given partial exposure of an object in time and constraints we have imposed, the expectation is that short duration grazing reduces trampling probabilities in comparison with continuous grazing. This result accrues because of high levels of redundant trampling in paddocks and because trampling is conditional on probability of exposure (v/T). The qualitative and quantitative predictions of the null models do not hold with partial exposure.

Competing Risks

Under field conditions, objects subject to livestock trampling might experience loss to other factors. Ground nests would be subject to predation, flooding, and trampling by wild ungulates. For example, Bareiss et al. (1986) observed 1 of 600 nests trampled when nontrampling losses destroyed ≥90% of sample nests.

Competing risks generally are expected to lower observed trampling rates, because an object lost to some other cause cannot be trampled. This assertion can be illustrated by assuming that trampling and nontrampling losses are not mutually exclusive and defining c as the probability of loss to a nontrampling cause. Then on any day of grazing, the probability that an object is lost to trampling or to a nontrampling cause is

$$P(\text{loss}) = q + c - b$$

where $0 \leq b \leq q$ and $0 \leq b \leq c$. The probability b includes (1) objects trampled that would have been lost to other causes without grazing and (2) objects lost to other causes that would have been trampled without other losses. The trampling rate observed in the field is therefore $<q$ if $b > 0$ (subtract some fraction of b from q).

The above arguments suggest that, in the presence of competing risks, quantitative predictions of the null models would in general be biased high. However, the qualitative prediction holds.

Nonrandom Grazing with Random Placement of Objects

Livestock do not graze randomly, but if they graze uniformly the underlying assumption of random grazing probably is acceptable and the qualitative and quantitative predictions of the null models would hold approximately. Practices are available to promote uniform grazing in research and management. If the assumption of uniform grazing is unacceptable, then we can conceptualize any single pasture (or paddock) as being stratified to the extent necessary to assume approximately uniform grazing within each stratum. The null models can then be applied to these strata.

Suppose a pasture consists of $i = 1, 2, ..., s$ strata subject to different uniform grazing intensities. Let the proportion of the pasture occupied by stratum i be a_i and let the proportion of time (T) spent grazing on stratum i be g_i. Trampling probabilities for each stratum can now be estimated using

$$P_i(\text{loss}) = 1 - (1 - q/(a_iA))^{g_ihT} \quad (5)$$

and a weighted average probability of trampling ($\bar{P}$) is

$$\bar{P} = \Sigma a_iP_i. \quad (6)$$

Note that a product a_iP_i is the probability that an object is in a stratum times the probability of loss given an object is in a stratum.

Because probability of trampling starts at zero and converges to one as time-based stocking rate increases for all models, predictions are identical at the extremes and quite similar at values near the extremes. Between the extreme probabilities (0 and 1), expected trampling loss is lower under nonrandom grazing than under random grazing (Fig. 1). This effect should arise because the strata with higher effective stocking rates are subject to more redundancy in trampling. Consider what would happen if all grazing took place on 1% of a pasture. The expectation is that ≤1% of the randomly dispersed objects would be trampled, whereas with enough time, 100% of objects could be trampled under random grazing over the entire pasture. Promotion of nonuniform grazing is possible in principle as a management method of reducing trampling loss. This could be accomplished by having some of the paddocks in a short duration grazing system with different areas and grazing each paddock the same number of days, or by holding the size of paddocks constant and grazing some a different number of days. Note that partial exposure of objects in time can be conceptualized as nonrandom grazing when one compares short duration and continuous grazing.

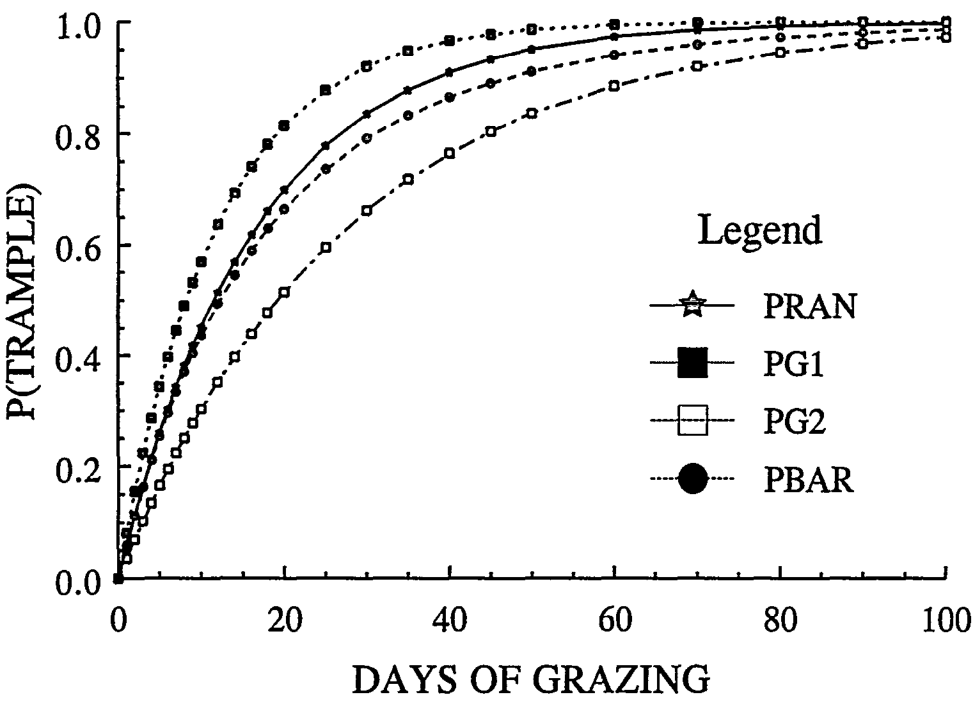

Fig. 1. Probability of trampling [P(TRAMPLE)] as a function of time in the presence of nonrandom grazing and random dispersion of objects vulnerable to trampling. The area is A = 100 ha, the base probability of trampling is q = 0.3, and the number of livestock is h = 20. Trampling probabilities are PRAN for random grazing, PG1 for grazing on the 50% of the pasture that receives 70% of livestock use, PG2 for grazing the 50% of the pasture that receives 30% of livestock use, and PBAR for the weighted average of PG1 and PG2.

Nonrandom Placement of Objects with Random Grazing

Define $j = 1, 2, ..., r$ strata that represent various degrees of clumping of vulnerable objects. Within each stratum, random placement of objects and random grazing will be assumed. Then the proportional area of each stratum (a_j) equals the expected proportional expenditure of time on the stratum and the probability of loss on each stratum is given by Equation (5) with $g_j = a_j$:

$$P_j(\text{loss}) = 1 - (1 - q/(a_jA))^{a_j hT}. \tag{7}$$

Let l_j be the probability that a vulnerable object occurs on stratum j with $\Sigma l_j = 1$. Then the estimated proportion of objects trampled in a single pasture or paddock is

$$\bar{P} = \Sigma l_j P_j. \tag{8}$$

Examination of Equation (7) reveals that as the adjusted base probability of trampling (q/a_iA) increases because of stratification, the time-based stocking rate (a_ihT) decreases on a stratum. These effects tend to offset each other and the probability of trampling is relatively constant among strata. As a result Equation (8) for all practical purposes results in a weighted average of a constant, which equals the constant, which is approximately equal to the probability of trampling given by the null model (Equation [2] with $n = 1$). Therefore, nonrandom placement of vulnerable objects with random grazing appears to have little practical effect on the quantitative and qualitative predictions of the null models.

Nonrandom Grazing and Nonrandom Placement of Objects

Two scenarios are possible concerning nonrandom grazing and nonrandom placement of vulnerable objects. The first is that placement and grazing are independent and the second is that nonrandom grazing governs placement. Whereas the first scenario might apply under some circumstances, we regard the second as the more general circumstance and model accordingly. The model developed below for the nonrandom-nonrandom circumstance may be used for vulnerable objects with different microhabitat requirements (e.g., bird species with different nesting cover requirements) and for dealing with hoof-placement decisions by cattle. These issues can be resolved through conceptualization and definition of strata (object placement, grazing intensity).

We have already developed theory for trampling probabilities in the presence of nonrandom grazing and random placement of objects [Equations (5) and (6)]. We need only modify Equation (6) to arrive at an estimate of average trampling probability under the nonrandom-nonrandom circumstance. Define l_i as the probability that a vulnerable object occurs in stratum i. Note that under random placement the proportion of a pasture occupied by a grazing stratum is also the probability that a vulnerable object occurs in the stratum ($a_i = l_i$). With nonrandom placement and nonrandom grazing we can replace a_i by l_i in Equation (6) to obtain

$$\bar{P} = \Sigma l_i P_i \tag{9}$$

where P_i is estimated by Equation (5).

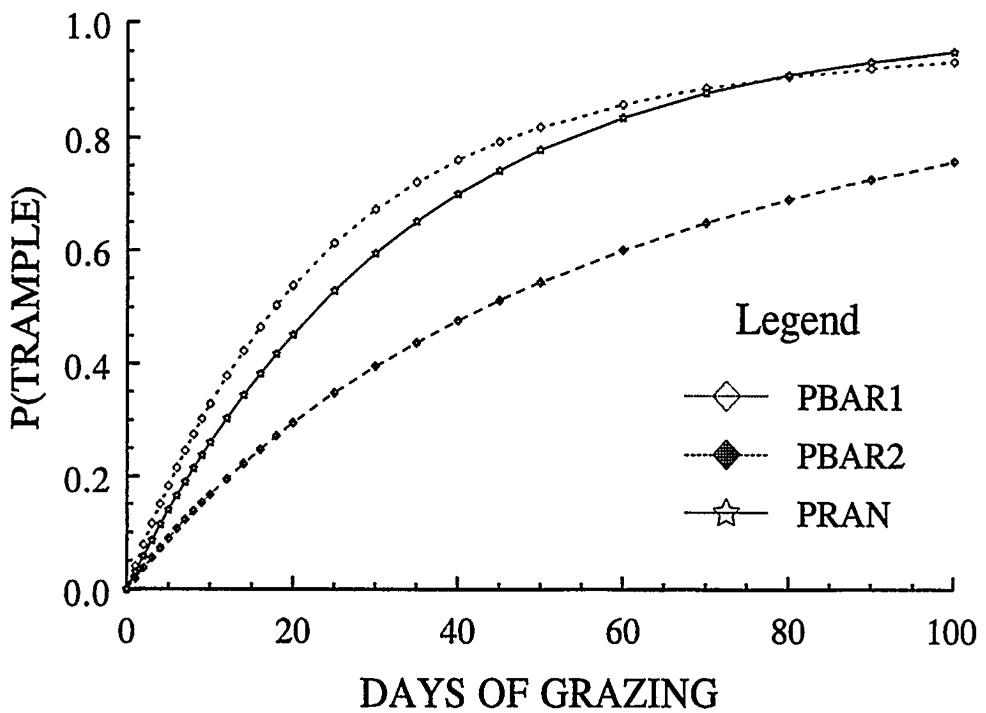

Fig. 2. Probability of trampling [P(TRAMPLE)] as a function of time in the presence of nonrandom grazing and nonrandom dispersion of objects vulnerable to trampling. The area is $A = 100$ ha, the base probability of trampling is $q = 0.3$, the number of livestock is $h = 10$, and the hypothetical pastures consist of 2 strata with different grazing intensities and densities of vulnerable objects. Trampling probabilities are PRAN for random grazing and random dispersion of objects, PBAR1 for a pasture with 80% of grazing and 80% of vulnerable objects on 50% of the pasture and 20% of grazing and 20% of objects on the second stratum, and PBAR2 for a different pasture with 80% of grazing and 20% of vulnerable objects on 50% of the pasture and 20% of grazing and 80% of objects on the second stratum.

No general statement about reliability of the qualitative and quantitative predictions of the null models can be made in the presence of nonrandom grazing and nonrandom object placement. The null models may over- or underestimate trampling probabilities when vulnerable objects clump in strata with heavier grazing or overestimate probabilities when vulnerable objects avoid strata with heavier grazing (Fig. 2).

Predictions vs. Empirical Results

Jensen et al. (1990) provide fully independent data and equations to test the prediction that similar time-based stocking rates result in similar trampling probabilities. They used clay pigeon targets to simulate ground nests so competing risks were not an issue. Their experiment consisted of 8 paddock sizes with systematic placement of targets at 10-m intervals in the center of experimental paddocks. The Jensen et al. (1990) results were consistent with the prediction of Equation (1). At a constant time-based stocking rate of 50 head-days ha^{-1}, the predicted probabilities of trampling were remarkably similar (Table 1) (CV = 6.1%). Variation was higher at 13–17 head-days ha^{-1} (CV = 49.7%) because of high trampling at 17 head-days ha^{-1}; trampling loss was quite similar at other time-based stocking rates within the specified range. Variation is expected in field studies because q is a function of weather, properties of vegetation cover, and chance factors.

Table 1. Probability of trampling under different grazing patterns with similar time-based stocking rates (head-days ha^{-1}) based on data from Jensen et al. (1990).

Time-based stocking rate Grazing pattern	Probability of trampling
50 head-days ha^{-1}	
5 head for 10 days	0.59
25 head for 2 days	0.66
50 head for 1 day	0.60
13-17 head-days ha^{-1}	
4 head for 4 days	0.18
8 head for 2 days	0.21
5 head for 3 days	0.18
13 head for 1 day	0.18
15 head for 1 day	0.23
17 head for 1 day	0.49

The independent data set of Koerth et al. (1983) provided an opportunity to test Equation (2). They evaluated trampling of clay targets on a continuously grazed pasture (32 ha) stocked with 4 steers for 48 days. Under an assumed base probability of trampling of $q = 0.0186$ (see below for justification of this number), Equation (2) predicts a trampling probability of 0.11. The value observed by Koerth et al. (1983) was 0.15.

Koerth et al. (1983) also evaluated trampling loss under short duration grazing (9 steers, 48 ha, 16 paddocks, 3 days grazing paddock^{-1}). Equation (2) predicts trampling loss of 0.17, whereas the observed value was 0.09.

Despite the restrictive assumptions underlying Equation (2), this model was consistent with the field results of Koerth et al. (1983). Confidence limits (95%) from the Koerth et al. data overlapped the predicted values. Equation (2) predicted higher trampling under rotation grazing at a higher time-based stocking rate (9 head-days ha^{-1}) than tested under continuous grazing (6 head-days ha^{-1}). The difference between the predicted and observed values possibly arose because the paddock layout in the Koerth et al. study fostered nonuniform grazing. Water was available at 1 end of a central alley in the grazing design. Regardless of which paddock was being grazed livestock activity was focused in the central alley. We demonstrated earlier that nonrandom grazing in the presence of random dispersion of vulnerable objects results in trampling rates lower than those predicted by the null models.

Base Probability of Trampling

The models presented above provide a general theoretical basis for study and management of trampling loss. The value of q needs to be known for quantitative predictions of trampling probability, but any reasonable value can be used to generate relative losses among grazing management strategies.

We analyzed data presented by Jensen et al. (1990) to determine an empirical value for q in the absence of competing risk losses. They modeled probability of loss as a function of time as follows:

$$P(\text{loss}) = 1 - \exp(-B_i t).$$

The coefficient B_i is specific to cattle density i (head ha^{-1}) and the quantity $\exp(-B_i t)$ is homologous to $(1 - q)^{ht}$ in our models. By solving their models for loss at $t = 1$, base trampling probability is estimated at

$$P(\text{loss}|1 \text{ head, } 1 \text{ ha, } 1 \text{ day}) = q = 1 - \exp(-B_i/h)$$

Based on 8 trials, q averaged 0.0186 + 0.00308 (SE) in the Jensen et al. (1990) data.

The estimated value of q can be considered the proportion of 10,000 m^2 that is trampled. It follows that 1 head of cattle tramples between 124 and 248 m^2 day^{-1} at the approximate 95% confidence level. Data presented by Bryant et al. (1982) suggest trampling of 99 m^2 per day if each hoofprint covers 78.5 cm^2 (the assumption on hoofprint size is ours). These arguments indicate that base trampling probability may lie between 0.01 and 0.03 for cattle.

Example Applications and Calculations

Consider a wildlife refuge that has 2 endangered species. One species benefits from the habitat changes (structural, compositional) associated with livestock grazing whereas the second (a small cactus) is vulnerable to trampling mortality. The manager must balance the benefits and risks of grazing in arriving at a decision on grazing management.

Suppose the refuge has 40,000 ha of grazing land and the recommended stocking rate is 50 ha AU^{-1} (800 cattle) for continuous, yearlong grazing. The refuge manager can estimate probability of trampling with Equation (2) for $n = 1$. The manager selects $q = 0.02$ as the base probability and finds that

$$P(\text{loss}) = 1 - (1 - 0.02/40{,}000)^{800(365)} = 0.136.$$

This result means that for 365 days of grazing by 800 head of cattle on 40,000 ha the estimated probability of trampling is 13.6%. If the refuge had a population of 1,000 vulnerable objects, the manager would project a loss of 136 from trampling. The reliability of this number is, of course, conditional on the accuracy of the value selected for q and fit to underlying assumptions.

The manager decides that a trampling loss rate of 0.136 would lead to population decline in the endangered species vulnerable to trampling. An annual loss rate of 0.05 would be acceptable, especially since grazing would benefit one endangered species. The problem is to estimate the number of cattle that will yield annual trampling loss of 0.05. This can be accomplished by solving Equation (2) for h given $P = 0.05$:

$$h = [\ln(1 - P)/\ln(1 - q/A)](1/T)$$
$$= [\ln(1 - 0.05)/\ln(1 - 0.02/40{,}000)](1/365)$$
$$\approx 281 \text{ head.}$$

As another example, consider a rancher who plans to institute a short-duration grazing regime on a 2,000-ha pasture currently grazed continuously with 100 cattle. The manager plans on installing 20 paddocks and grazing each for 7 days. They will double the stocking rate to take advantage of hoof-action and to pay for capital investments. The rancher derives income from lease hunting for northern bobwhites (*Colinus virginianus*) and is concerned about the potential effects of the decision on nest trampling.

Equations (3) and (4) provide models for estimating the effects of short duration grazing on nest trampling. Bobwhites require about 42 days to lay and incubate a clutch, so $v = 42$. The time for 1 rotation is 140 days or about the length of the laying season (Guthery et al. 1988). Under continuous grazing at $q = 0.02$ by Equation (3)

$$P(\text{loss}) = 1 - (1 - 0.02/2{,}000)^{100(42)}$$
$$= 0.041.$$

Under the proposed short duration grazing with doubled stocking rate,

$$P(\text{loss}) = (42/140)[(1 - (1 - 20(0.02)/2000)^{200(140)/20}]$$
$$= 0.073.$$

The increase in nest trampling associated with short duration grazing would seem inconsequential to quail populations. However, the effects of doubled stocking rate on habitat should be considered.

Discussion

The theoretical background we have described for study and management of trampling loss provides a new perspective on the empirical literature on trampling. We use the work of Koerth et al. (1983) as an example. Our intent is to show how the theoretical models might influence perspectives and interpretations.

Koerth et al. (1983:386) concluded that "there appears to be no reason for concern that trampling losses by cattle will be higher under the [short duration grazing] regime used in this study than under [continuous] grazing, even though stocking rates were higher under [short duration grazing]. By inference, trampling losses should be lower under [short duration grazing] than under [continuous] grazing at similar stocking rates." The null models we developed are justifiable for the Koerth et al. (1983) study, because they used clay targets not subject to competing risks or partial exposure in time. Predictions of the models are contrary to the above conclusions given full exposure in time, i.e., we expect trampling loss to increase with time-based stocking rate for vulnerable objects such as cactus. However, predicted trampling probabilities do not increase in proportion to increases in stocking rate. Whether statistical differences will be observed in the field depends on variability in trampling and on the amount of time objects are vulnerable. If exposure period is short or long, all types of grazing treatments can result in similar trampling probabilities.

Koerth et al. (1983:363) also concluded, "the only alternative to reduce trampling losses under [continuous] grazing is to lower the stocking rate. Under [short duration grazing], however, increasing the number of pastures while holding the stocking rate and days of grazing per pasture constant should decrease trampling losses. This would occur because a smaller percentage of the area would be grazed during any laying and incubation period." This conclusion is consistent with theoretical expectations given partial exposure in time (Equations [3] and [4]), but is not consistent with theoretical expectations given continuous exposure during a complete short duration rotation (Equation [2]).

We advocate using the models developed in this paper for hypothesis generation and testing in research. These models generate *a priori* hypotheses about the effects of time-based stocking rate on trampling loss. *A priori* hypotheses are a condition of quality science.

Finally, we observe that the issue of trampling loss has complexities that extend beyond the probabilistic background we have presented. These complexities involve habitat selection and use and adaptations of plants and animals vulnerable to trampling at some stage in their life history. We hope the models will assist in study and management of trampling in this broader context.

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