Factors Associated with Succession of Abandoned Agricultural Lands along the Lower Missouri River, U.S.A.

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Abstract

The 1993 flood of the Missouri River led to the abandonment of agriculture on considerable land in the floodplain. This abandonment led to a restoration opportunity for the U.S. Federal Government, purchasing those lands being sold by farmers. Restoration of this floodplain is complicated, however, by an imperfect understanding of its past environmental and vegetative conditions. We examined environmental conditions associated with the current placement of young forests and wet prairies as a guide to the potential successional trajectory for abandoned agricultural land subject to flooding. We used Bayesian mixed-effects logistic regression to examine the effects of flood frequency, soil drainage, distance from the main channel, and elevation on whether a site was in wet prairie or in forest. Study site was included as a random effect, controlling for site-specific differences not measured in our study. We found, after controlling for the effect of site, that early-successional forest sites were closer to the river and at a lower elevation but occurred on drier soils than wet prairie. In a regulated river such as the lower Missouri River, wet prairie sites are relatively isolated from the main channel compared to early-successional forest, despite occurring on relatively moister soils. The modeled results from this study may be used to predict the potential successional fate of the acquired agricultural lands, and along with information on wildlife assemblages associated with wet prairie and forest can be used to predict potential benefit of these acquisitions to wildlife conservation.

Key words: **flooding, mixed-effects models, wet prairie, wildlife habitat, young forest.**

Introduction

The 1993 flood of the Missouri River destroyed levees and ruined farmland by scouring fields and depositing sands, leading to the abandonment of agriculture in many areas in the floodplain (Galat et al. 1998). The Final Environmental Impact Statement of the Big Muddy National Fish and Wildlife Refuge in Missouri, U.S.A., presented the possibility of incorporating recent abandoned agricultural land into the refuge, expanding the size of the refuge from 6,729 ha to approximately 24,280 ha (U.S. Fish and Wildlife Service 1999). It is of interest to the refuge to be able to project the potential successional trajectory of these abandoned agricultural lands toward forest or wet prairie habitats, as the wildlife assemblage is expected to differ between these two habitats (Thogmartin et al. 2006). Unfortunately, the restoration of this floodplain is complicated by an imperfect understanding of its history and ecology (i.e., its past environmental and vegetative conditions).

Our objective was to examine the environmental conditions associated with establishment of young forests versus wet prairie in abandoned agricultural land subject to flooding. Flood pulses are crucial in seed dispersal, plant establishment, nutrient cycling, scouring, sediment deposition, and maintenance of species richness (Johnson et al. 1976; Skoglund 1990; Stromberg et al. 1993; Nilsson et al. 1997; Friedman & Auble 1999; Middleton 1999, 2002). As a result, floods govern much of the spatial pattern in vegetation and topography in floodplains (Bayley 1995; Miller et al. 1995; Ward & Stanford 1995; Gergel et al. 2002).

We hypothesized that factors associated with flooding would preclude succession of abandoned agricultural sites to climax forest along the lower Missouri River. We surmised that sites closer to the river would be subjected to greater frequency and severity of flooding and remain in an early successional state (i.e., wet prairie) by frequent

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scouring. Alternatively, sites further from the river would presumably be less affected by flooding and have the potential to succeed to early-successional forest conditions. To examine this hypothesis, we modeled factors associated with sites that were wet prairie or early-successional forest as a hierarchical, mixed-effects model to identify key characteristics that would prove useful for predicting the potential successional direction of the lands acquired by the refuge.

Methods

Study Area

We chose seven study sites within the lower Missouri River alluvial floodplain, stretching from central Missouri to east central Missouri (near St. Louis; Table 1). These seven sites were located in three Missouri Department of Conservation Areas (Overton South, Eagle Bluffs, and Howell Island) and a U.S. Fish and Wildlife Service refuge (Big Muddy National Fish and Wildlife Refuge).

The study region is characterized by loess deposits ranging from 3- to 27-m-deep, overlaying limestone bedrock and bounded by limestone and sandstone bluffs. Soils are generally moderately well drained to well drained, consisting of Haynie and Waldron Soil Series soils. The river floodplain varies in width from 3 to 16 km; low river benches, terraces, and the remains of former river channels are common (U.S. Fish and Wildlife Service 1999).

Land cover at the various study sites consisted of wet prairie and early-successional forest. Floodplain wet prairie, possessing less than 5% tree coverage, comprised herbaceous and emergent plants and grasses, including horseweed (*Conyza* spp.), aster (*Symphyotrichum* spp.), goldenrod (*Solidago* spp.), smartweed (*Polygonum* spp.), pigweed (*Amaranthus* spp.), bulrushes (*Scirpus* spp.), cattail (*Typha* spp.), prairie cordgrass (*Spartina* spp.), sedges (*Carex* spp., *Cyperus* spp., *Eleocharis* spp.), rice cutgrass (*Leersia* spp.), Reed canarygrass (*Phalaris arundinacea*), and millet (*Echinochloa* spp.) (Nelson 1987; Young et al. 2004). Early-successional forest comprised densely forested habitat, with trees less than 10 years of age. Dominant tree species were Eastern cottonwood (*Populus deltoides*), willows (*Salix* spp.), Box elder (*Acer negundo*), ash (*Fraxinus* spp.), dogwood (*Cornus* spp.), and mulberry (*Morus* spp.).

Environmental Covariates

Within each study area, there were 0–24 prairie sites and 4–44 forest sites (Table 1). These sites within study areas were specific locations in which information regarding flood frequency, drainage condition of the soil, distance to the main channel of the Missouri River, and elevation was determined. Elevation was acquired from EarthData International, LLC (Gaithersburg, MD), as a 3-cm vertical resolution, 4.57-m horizontal resolution digital elevation

Table 1. Location, sample sizes, and mean (minimum and maximum) environmental characteristics associated with seven study areas along the lower Missouri River, 2002–2004.

					Wet Prairie				Young Forest			
Study Area	*Site Acronym*	*Longitude*	*Latitude*	*Number of Prairie/ Forest Sites*	*Flood Frequency*[a]	*Soil Drainage Class*[b]	*Distance From Main Channel (m)*	*Elevation Difference (m)*	*Flood Frequency*[a]	*Soil Drainage Class*[b]	*Distance From Main Channel (m)*	*Elevation Difference (m)*
Jameson Island	JAM	92.9	39.1	0/44					0.6 (0–1)	3.3 (1–4)	615 (126–1,568)	1.4 (−0.3 to 2.7)
Lisbon Bottoms	LIS	92.9	39.1	3/35	1	2.0 (1–4)	612 (291–855)	1.4 (1.1–2.0)	1.2 (1–2)	1.1 (0–4)	892 (177–1,668)	1.3 (0.2–2.6)
Overton Bottoms North	OVN	92.6	39	22/16	1	3.6 (1–5)	1498 (822–2,228)	1.8 (0.5–2.9)	1	2.8 (0–5)	552 (171–1,342)	1.6 (0.5–2.6)
Overton Bottoms South	OVS	92.5	38.9	24/31	1	3.4 (0–5)	1,212 (123–2,294)	3.0 (1.7–4.1)	1.4 (1–2)	2.6 (1–5)	346 (0–1,296)	2.6 (1.1–4.4)
Eagle Bluffs	EBL	92.5	38.9	0/6					1	3.2 (3–4)	345 (136–495)	3.2 (2.0–4.4)
St Aubert Island	STA	91.8	38.7	0/4					2	4	300 (216–415)	1.2 (0.6–1.8)
Howell Island	HOW	90.7	38.7	4/4	0	1	679 (655–699)	5.8 (5.6–5.9)	0.5 (0–1)	2.5 (1–4)	487 (174–808)	4.0 (2.6–6.6)

[a] Flood frequency is an ordinal variable varying between 0 (rare) and 2 (frequent).

[b] Soil drainage class is an ordinal variable varying between 0 (excessively drained) and 5 (very poorly drained).

model for the seven study areas. Flood frequency and drainage condition of the soil were obtained from SSURGO soils coverages (Flood Frequency Class [Maximum] and Soil Drainage Class [Wettest], respectively, in SSURGO; http://soildatamart.ncrs.usda.gov/SSURGOMetadata.aspx). Flood frequency was the annual probability of a flood event expressed as a class (rare [0, <5% chance of flooding], occasional [1, 5–50% chance of flooding], and frequent [2, >50% chance of flooding]). The natural drainage condition of the soil described the frequency and duration of wet periods as a class (excessively drained [1], well drained [2], moderately well drained [3], somewhat poorly drained [4], very poorly drained [5]).

Because multiple sites often occurred within each study area, we treated study area as a random effect, accommodating effects imposed by unmeasured variables at the level of the study area that may cause correlated effect in the response. This in turn allowed for the unbiased assessment of the effect of measured environmental covariates on habitat (wet prairie and young forest). Flood frequency, drainage condition of the soil, distance to the main channel of the Missouri River, and elevation were included as fixed effect covariates. Because the mean elevation of the study areas declines as one moves west to east along the Missouri River, we standardized the survey point elevation by differencing out the study area mean elevation. Thus, sites with a negative value were low relative to the area mean elevation, whereas positive values were from locations high relative to the area mean elevation.

Data Analysis

We followed a Bayesian approach with fixed and random effects for modeling probability of a site succeeding to wet prairie or forest. The form of the model was as follows:

$$\begin{aligned}\operatorname{logit}(p_{ik}) &= \ln(p_{ik}/(1 - p_{ik}))\\ &= \beta_0 + U_{ok} + \beta_1 x_{1i} + \ldots + \beta_j x_{ji} + \varepsilon_{ijk}\end{aligned}$$

where $i = 1 \ldots n$, β_j are the slopes for the fixed effects x_{ji}, U_{ok} is the random effect associated with k study area, and $p_{ik} = \Pr(Y_{ik} = 1)$. Diffuse or noninformative priors and hyperpriors were assigned to each parameter to represent an initial expectation of the variables on land cover class. Fitting and prediction were conducted in WinBUGS 1.4.1 (Spiegelhalter et al. 2003), a statistical package for conducting Bayesian inference with Markov chain Monte Carlo. For each model, we ran the Markov chain until convergence occurred (1,000 iterations) and an additional 50,000 iterations past convergence. This chain creation was conducted three times to create replicate chains for the Gelman–Rubin diagnostic (Spiegelhalter et al. 2003), comparing within- and between-chain variability. Of the 150,000 samples collected (3 chains × 50,000 iterations), parameter estimates were summarized for every fifth iteration of the iteration histories to reduce within-chain autocorrelation (final $n = 30{,}000$). Multicollinearity in the environmental variables was guarded against by inspecting the multichain iteration histories and the Gelman–Rubin diagnostic plots of the model parameters.

We used an information-theoretic approach to our modeling by comparing the Deviance Information Criterion (DIC) among models; DIC is an information criterion analogous to Akaike's Information Criterion, with the most parsimonious model possessing the smallest DIC (Spiegelhalter et al. 2002). Our model set included a null model, a model with the four main fixed effects and then models with one, two, and three 2-way interaction terms. In each of the models, we included a random effect associated with the seven study sites. We did not fit more than three 2-way interactions or any interactions of higher order because of difficulties with model fit and interpretability.

Results

The best model was one that possessed each of the four main effects and an interaction term of soil drainage class × elevation difference (Table 2). A closely competing model possessed the same constituents, but it also contained the interaction terms flood frequency × soil drainage class and flood frequency × elevation difference. A model excluding all main effects, except for distance from the main channel, was third best. Subsequent models were greater than 13 DIC from the best model, indicating that they were essentially irrelevant to explaining the patterns we observed. Because the interaction terms associated with flood frequency were subtle and not credibly different from 0 and because the best model had odds nearly 2:1 in its favor over that of the second best model

Table 2. Competing regression models ranked by DIC for estimating probability of an acquired agricultural site along the lower Missouri River succeeding to wet prairie or forest.

Model	*DIC*	*ΔDIC*	*ω*
Flood frequency + drainage class + distance from main channel + elevation difference + elevation difference × soil drainage class (sites)	125.3	0.0	0.59
Flood frequency + drainage class + distance from main channel + elevation difference + elevation difference × soil drainage class + flood frequency × soil drainage class + flood frequency × elevation difference (sites)	126.5	1.2	0.32
Distance from main channel (sites)	129.2	3.9	0.08

ΔDIC is the difference in DIC between the best model and the model in question; ω is DIC weights indicating the relative likelihood of the model and sum to 1.0 across models.

and 7.5:1 odds over that of the third best model, we restricted subsequent inference to the best model.

Study areas differed in their response to whether a site was wet prairie or a forest beyond the effects of the four environmental factors we studied. Overton Bottoms North and South were predisposed to wet prairie cover. Jameson Island was predisposed to forest (Fig. 1), but this was a statistical artifact resulting from no sites occurring in wet prairie at this location. There was a marginal interaction of soil drainage class and elevation (Table 3); it appeared that wetter, higher sites had a higher probability of occurring as wet prairie compared to lower, drier sites. Ponded soil, or soils wet to the surface (Soil Drainage Class 4, Somewhat Poorly Drained soils), was almost entirely wet prairie rather than early-successional forest. Some circumspection is required for this interaction term as its credibility interval marginally bounded zero for the parameter estimate (and one for the odds ratio; Fig. 2e). The coefficient with the greatest magnitude and tightest credibility limit belonged to that of the distance to the main channel; as the distance from the main channel increased, the probability of a site being wet prairie increased (Fig. 3a). Quantitatively, the probability of being in forest declined by 15% for every 100 m increase in distance from the main channel, whereas the probability of being in forest declined by approximately 7% for every 0.1 m increase in elevation. Flood frequency had little apparent influence on whether a site was wet prairie or early-successional forest.

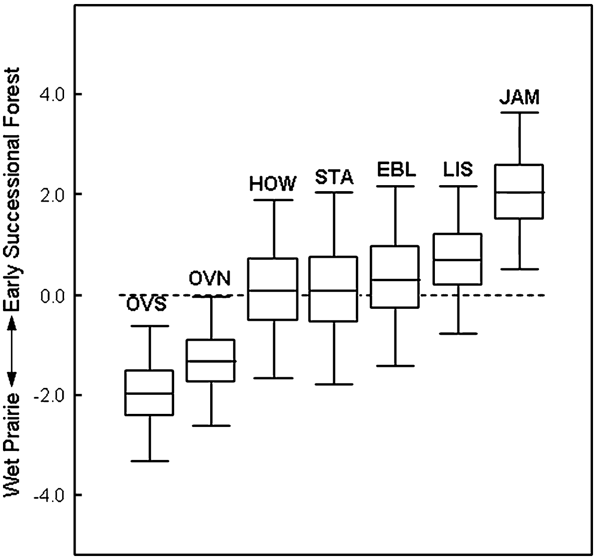

Figure 1. Boxplot of the effect of study area on the relationship between wet prairie and early-successional floodplain forest. Boxes represent the interquartile ranges bisected by the median study area effect; the arms extend to the 2.5 and 97.5% quantiles. See Table 1 for study area acronyms. Values on the negative side favor the formation of wet prairie, whereas those on the positive side favor the creation of early-successional forest.

Discussion

The result that sites closest to the main channel were more likely to occur as forest is counterintuitive to our a priori expectation, as we had suspected that near-river sites would be affected by flooding and scouring and thus set back to an early successional state (McKenzie 1936; Sigafoos 1964). There are reasons, however, to believe that this natural process can no longer be the basis for our a priori perspective.

It is generally understood that operation of floodplain protection projects alters the hydrologic regime of a river system (Dynesius & Nilsson 1994; Nilsson & Svedmark 2002) and results in large disruptions to the biota of the attendant floodplain (Nilsson & Dynesius 1994). There are approximately 7,000 structures on the lower Missouri River as a result of the Bank Stabilization and Navigation Project (R. C. Hargrave, 2007, U.S. Corps of Engineers, personal communication). Two major alterations resulting from such structures are a reduction of peak annual flow (mean annual flood), because of impoundment of excess run-off, and reduction of sediment load, because of sediment deposition in the upstream reservoirs (Johnson et al. 1982). Streamflow for June (early to mid-growing season) is now lower than June flows recorded in the drought years of the 1930s (Johnson et al. 1982). At other times of the growing season, excess water is distributed to nearby agricultural lands rather than to an increased in-stream flow rate. This reduced flow results in a reduction in bank erosion (25% of pre-dam levels), reduced river meandering (accretion rates having fallen to 1%), and, in turn, to the prolonged persistence of forest vegetation. Further, the reduction in peak flows reduces or eliminates recharge of upper soil layers, creating perpetual drought conditions in floodplain soils (Cooper et al. 2003, Williams & Cooper 2005), which may be nonconducive to riparian grassland formation (Henszey et al. 2004). However, these drought conditions are also linked to declines in riparian cottonwood (Reily & Johnson 1982; Williams & Cooper 2005), a major component in the early-successional forests on the lower Missouri River.

Once early floodplain forests are established, post-dam construction flow patterns are out of phase with vernal growth patterns typical of these communities. Cottonwood and willow species germinate and persist on exposed alluvium resulting from river meandering. But when these early-successional communities are uneroded, they mature, with the overstory being replaced by admixtures of Boxelder, Silver maple, Pin oak, Swamp white oak, and Slippery elm, and the occasional large cottonwood. Therefore, flooding regimes, natural or otherwise, will be necessary to maintain vegetative and wildlife communities most commonly associated with early-successional floodplain forest.

Most flooding, however, has been eliminated on terraces more than 2 m above mean river level, reducing moisture and nutrient influx to higher terraces. This 2-m

Table 3. Parameter estimates (slope and 95% credibility intervals) for the hierarchical mixed-effects logistic regression describing the differences between wet prairie and forest on the lower Missouri River.

Parameter	*2.5%*	*Median*	*97.5%*	*2.5%*	*OR*	*97.5%*
Intercept	−0.696	1.523	3.890	0.499	4.586	48.911
Flood frequency	−0.630	0.985	2.744	0.533	2.677	15.549
Soil drainage class	−0.718	−0.147	0.424	0.488	0.864	1.527
Distance from main channel	−2.566	−1.837	−1.190	0.077	0.159	0.304
Elevation difference	−2.785	−1.450	−0.232	0.062	0.235	0.793
Drainage × elevation	−0.023	0.524	1.087	0.977	1.688	2.965
Study (EBL)	−1.408	0.320	2.162	0.245	1.378	8.688
Study (HOW)	−1.636	0.092	1.874	0.195	1.097	6.514
Study (JAM)	0.515	2.040	3.636	1.673	7.691	37.940
Study (LIS)	−0.762	0.687	2.163	0.467	1.989	8.697
Study (OVN)	−2.578	−1.318	−0.043	0.076	0.268	0.958
Study (OVS)	−3.326	−1.948	−0.628	0.036	0.143	0.534
Study (STA)	−1.778	0.105	2.006	0.169	1.110	7.434

The odds ratios for wet prairie and their 95% credibility intervals are included as well. Confidence intervals excluding zero (parameter estimates) or one (OR) were deemed important. See Table 1 for study area acronyms.

benchmark represents a threshold in the prediction between wet prairie and early-successional forest. Sites within 2-m elevation of the main channel were more likely to be early-successional forest sites. Perhaps unsurprising then was that soil drainage and flood frequency did not seem to influence the classification of a lower Missouri River site into wet prairie or forest in this highly altered habitat. It appears that intermittent or infrequent flooding (as would occur for sites of <2 m difference in elevation) may be sufficient for determining the fate of a floodplain location. Our notion of frequent scouring and overtopping by floods leading to conditions favorable to wet prairie (McKenzie 1936; Sigafoos 1964) are discounted; thus, we are compelled to look elsewhere to explain the occurrence of wet prairie in the lower Missouri River floodplain.

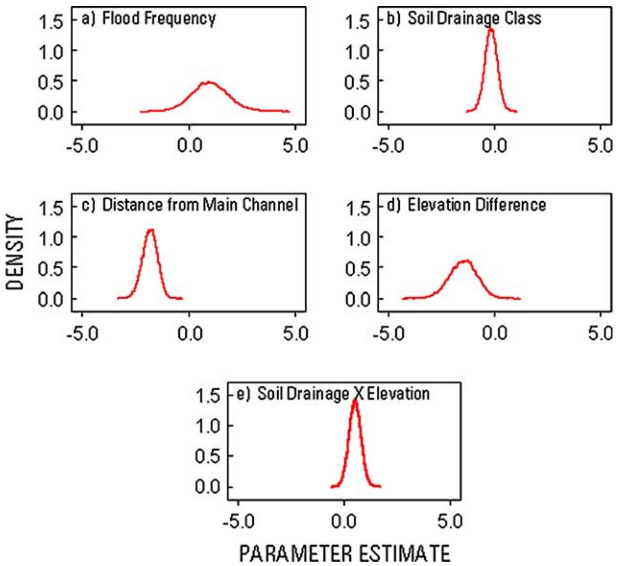

Figure 2. Plots of the posterior marginal sample distributions of the fixed effects (a–e) from the hierarchical mixed-effects logistic regression describing the difference between wet prairie and early-successional forest along the lower Missouri River. The magnitude, width, and location of the posterior distributions show the effect of the covariates relative to the uninformed or flat prior distribution centered at zero mean that was initially assumed for each covariate.

Differences between study areas that were unattributable to the four environmental factors we studied suggest that there are additional factors influencing whether abandoned agricultural sites naturally restore to wet prairie or early-successional forest. Site-level study into these factors is warranted; additional candidates include soil composition, subsurface water gradients, and water table depth, among others. Important drivers of floodplain vegetative composition that we were not able to examine were flood duration (Middleton 2002), hydrochory or plant dispersal by water (Middleton 2000; Merritt &Wohl 2002, 2006), and composition of the seed bank (Middleton 1999, 2000; Goodson et al. 2001). In addition, rather than upstream effects on local results, in- and near-channel modifications (channel training/wing dykes, mainline and setback levees) may have important, local influences on lateral disturbance fluxes (Galat et al. 1998). Overton Bottoms North, for instance, one of the sites with a strong site-level effect on the model results, is the location of reconstructed side channels (G. Covington, 2007, U.S. Army Corps of Engineers, personal communication). These in- and near-channel modifications have notably altered the relations between stage and discharge, both in terms of stages at low flows (notably lower) and stages at high flows (notably higher) (B. R. Ickes, 2007, U.S. Geological Survey, personal observation). Channel conveyance capacity attributable to channel training and resulting bed scour is reduced. Lower stages at low flows (summer growing season) can also notably affect near-channel hydrogeology dynamics and can also explain shifts toward more xeric environments within habitat nearest the main channel.

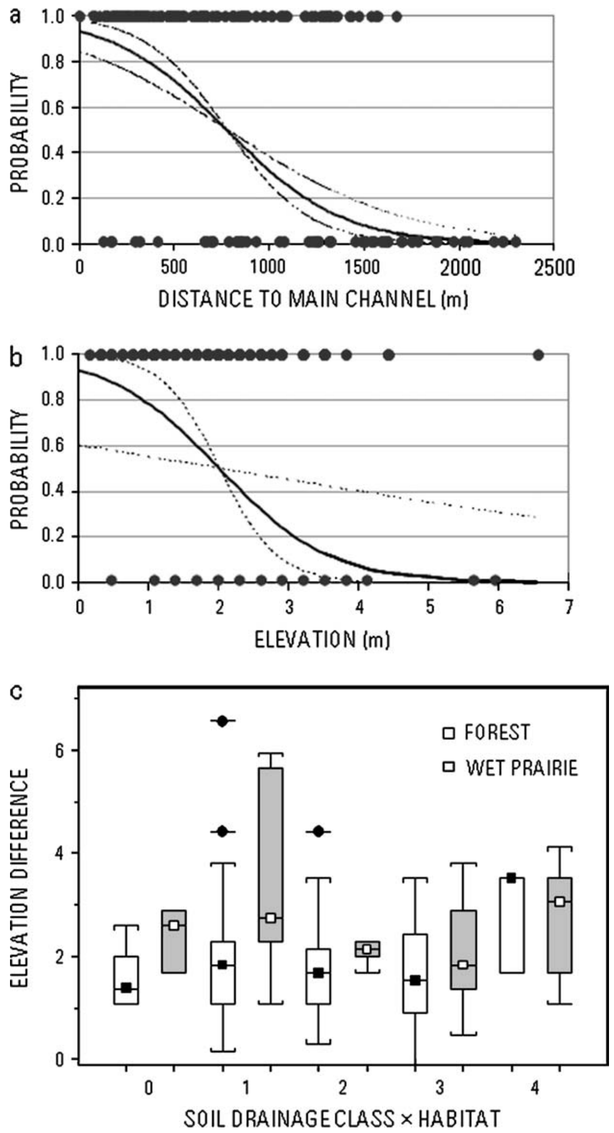

Figure 3. The probability of a lower Missouri River site being forest (1) rather than wet prairie (0) declined (a) with distance from the main channel and (b) an increase in the difference between site elevation and that of the river. Black dots are the observed occurrences in each class. (c) The interaction of the difference in elevation and soil drainage class (ordered from driest [0] to wettest [4]) had a marginal influence on discriminating between wet prairie and early-successional forest (note the near absence of early-successional forest in the wettest soil).

The value of predictive models we identified is that we can now project these models onto the landscape, producing spatial predictions of potential successional fate for the agricultural lands that the refuge acquires as a result of its long-term planning process. When coupled with information regarding the composition of the wildlife community associated with wet prairie and young forest habitat (Thogmartin et al. 2006), the ecological value of these land purchases can be elucidated. In a science-based management framework, such information is essential for efficient stewardship.

Implications for Practice

- Vegetational succession in the floodplain of regulated rivers does not follow a priori expectations resulting from an understanding of successional dynamics on uncontrolled rivers.
- In the absence of regular flooding, abandoned agricultural lands in floodplains similar to the lower Missouri River are more likely to succeed to forest if they are closer and nearer to the elevation of the main channel.
- Conversely, moist soil sites further and at a higher elevation than the main channel are more likely to succeed to wet prairie.
- Models are a useful tool for predicting the relative merit of land acquisition by natural resource agencies. Given predictions regarding the potential successional fate of abandoned agricultural lands, the consequences of such acquisitions can then be inferred for other ecosystem services such as wildlife conservation.

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