Articles

Quantile Equivalence to Evaluate Compliance With Habitat Management Objectives

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Abstract

Equivalence estimated with linear quantile regression was used to evaluate compliance with habitat management objectives at Arapaho National Wildlife Refuge based on monitoring data collected in upland (5,781 ha; n = 511 transects) and riparian and meadow (2,856 ha, n = 389 transects) habitats from 2005 to 2008. Quantiles were used because the management objectives specified proportions of the habitat area that needed to comply with vegetation criteria. The linear model was used to obtain estimates that were averaged across 4 y. The equivalence testing framework allowed us to interpret confidence intervals for estimated proportions with respect to intervals of vegetative criteria (equivalence regions) in either a liberal, benefit-of-doubt or conservative, fail-safe approach associated with minimizing alternative risks. Simple Boolean conditional arguments were used to combine the quantile equivalence results for individual vegetation components into a joint statement for the multivariable management objectives. For example, management objective 2A required at least 809 ha of upland habitat with a shrub composition ≥0.70 sagebrush (*Artemisia* spp.), 20–30% canopy cover of sagebrush ≥25 cm in height, ≥20% canopy cover of grasses, and ≥10% canopy cover of forbs on average over 4 y. Shrub composition and canopy cover of grass each were readily met on >3,000 ha under either conservative or liberal interpretations of sampling variability. However, there were only 809–1,214 ha (conservative to liberal) with ≥10% forb canopy cover and 405–1,098 ha with 20–30% canopy cover of sagebrush ≥25 cm in height. Only 91–180 ha of uplands simultaneously met criteria for all four components, primarily because canopy cover of sagebrush and forbs was inversely related when considered at the spatial scale (30 m) of a sample transect. We demonstrate how the quantile equivalence analyses also can help refine the numerical specification of habitat objectives and explore specification of spatial scales for objectives with respect to sampling scales used to evaluate those objectives.

Keywords: equivalence testing; habitat; quantiles; refuges; Comprehensive Conservation Plans

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Introduction

Individual units of the National Wildlife Refuge System administered by the U.S. Fish and Wildlife Service (USFWS) are in the process of developing Comprehensive Conservation Plans (CCPs) as required by the 1997 National Wildlife Refuge System Improvement Act (Schroeder 2006, 2008). The primary intent of this legislation is to promote development of credible and defensible management goals and objectives that are directly linked to achieving the purposes established for each National Wildlife Refuge (hereafter Refuge). The USFWS policy regarding objectives specified in CCPs requires Refuges to "develop detailed, measurable

objectives using available scientific literature and other appropriate information" that meets Refuge purpose and goals (USFWS 2000). One important use of detailed objectives is to facilitate development of monitoring protocols that can be used to track progress in achieving goals and evaluate the effectiveness of management strategies. Formulation of habitat-based goals and objectives has been encouraged at many Refuges because most management (e.g., prescribed fire, grazing, water management) implemented on Refuges influences wildlife populations indirectly by altering some habitat element (e.g., vegetation structure).

Although USFWS policies dictate that well-defined, measurable criteria based on best scientific information related to relevant ecological processes and biological responses are incorporated into CCPs (Schroeder 2006, 2008), there is less guidance on how Refuges should actually collect and evaluate data to monitor compliance with management objectives. Therefore, we developed an analysis protocol based on quantile equivalence testing (Cade 2011). We demonstrate how to implement and interpret this method by using data collected at Arapaho National Wildlife Refuge (ANWR) from 2005 to 2008 to evaluate compliance with habitat management objectives in their CCP (USFWS 2004). Quantile equivalence allowed us to determine the proportion of total area of habitat that met an interval of acceptable conditions for components of an objective while accounting for the sampling variation of the estimates. The estimated proportions for multiple components (e.g., cover, composition) were then combined using Boolean conditional statements to provide a simultaneous assessment for the multiple criteria defining a multivariable habitat management objective.

We present a basic set of procedures for using quantile equivalence to evaluate monitoring data with respect to management objectives and demonstrate the approach and interpretations possible with our application to the habitat management objectives at ANWR. Many other Refuges have similarly specified habitat management objectives; thus, we believe our approach is sufficiently general that it may be extended to other evaluations of habitat management objectives. Another extension of this analysis is to help land managers revise and improve how they specify management objectives that involve relating measurable criteria to intervals of acceptable values. The inherent variability of ecological processes coupled with a range of acceptable outcomes implies that reasonable management objectives will often need to be specified and evaluated as intervals of values.

Study Area and Management Objectives

The ANWR is located at elevations from 2,408 to 2,530 m within the 1,554-km^2 intermountain basin of northwestern Colorado known as North Park. It was established in 1967 primarily as nesting and rearing habitat for migratory birds. The ANWR is composed of 5,781 ha of upland shrub–steppe dominated by sagebrush (*Artemisia* spp.), perennial bunchgrasses, and forbs; 1,086 ha of meadow habitat that includes grasslands and old hay meadows that were historically irrigated; 1,770 ha of riparian habitat along the channel, floodplain, and upland fringe of the Illinois River and Spring Creek; and 333 ha of natural and created wetland habitats (Figure 1; USFWS 2004). Details of the plant taxa found at ANWR are provided in the CCP (USFWS 2004). Cattle grazing has been allowed on the Refuge for many years. During the years (2005–2008) of our monitoring analyses, there were 3,614–4,973 animal unit months grazing 24–32% of upland and 48–68% of meadow and riparian habitats from mid-May to early November. Other ongoing management actions that are reflected in the vegetation data include two prescribed burns and irrigation of meadow and riparian habitats.

The CCP for ANWR (USFWS 2004) includes habitat-based goals and associated objectives for all habitats. Objectives were developed based on quantitative habitat requirements (e.g., minimum area, vegetation composition) of focal or indicator species that were selected for each habitat type. This information was obtained by conducting a search of the scientific literature and unpublished reports. Details of all focal wildlife species considered in ANWR and their habitat requirements are in the CCP (USFWS 2004). Constructed ponds and their wetland habitats were not part of our monitoring analyses.

Management objectives specified for the meadow and riparian habitats at ANWR were developed to provide resources for nesting waterfowl, shorebirds, songbirds, greater sage grouse *Centrocercus urophasianus* broods, elk *Cervus elaphus*, pronghorn *Antilocapra americana*, and coyote *Canis latrans*. Although meadow and riparian habitats were distinguished and areas were mapped separately, they have similar intervals of acceptable vegetation conditions specified for management objectives, with the exception of willow (*Salix* spp.) cover in riparian habitats. The combined 2,856 ha of meadow and riparian habitats have two management objectives (USFWS 2004): 1A provides 2,137–2,305 ha, over a 5-y average, of a grass and forb plant community with a grass : forb ratio of 75:25, with a visual obstruction reading (VOR) of 1–3 dm, 0–10 cm of duff depth, and $\leq$5% bare ground; and 1B provides 340–492 ha, over a 5-y average, of a grass and forb plant community with a grass : forb ratio of 75:25, with a VOR >3 dm, 10–20 cm of duff depth, and $\leq$5% bare ground. The riparian habitats had the additional condition of requiring <40% canopy cover of willows by 2019 and 2009, respectively, for objectives 1A and 1B.

Management objectives specified for the upland habitats at ANWR were developed primarily to provide resources for greater sage grouse, large mammals, and other species associated with shrub–steppe (USFWS 2004). The 5,781 ha of the upland habitats have two management objectives (USFWS 2004): 2A provides 809 ha, over a 5-y average, of shrubs ($\geq$0.70 sagebrush) >25 cm in height with 20–30% canopy cover, >20% canopy cover of grasses, and >10% canopy cover of forbs; and 2B provides 809 ha, over a 5-y average, of shrubs ($\geq$0.70 sagebrush) >40 cm in height with >30%

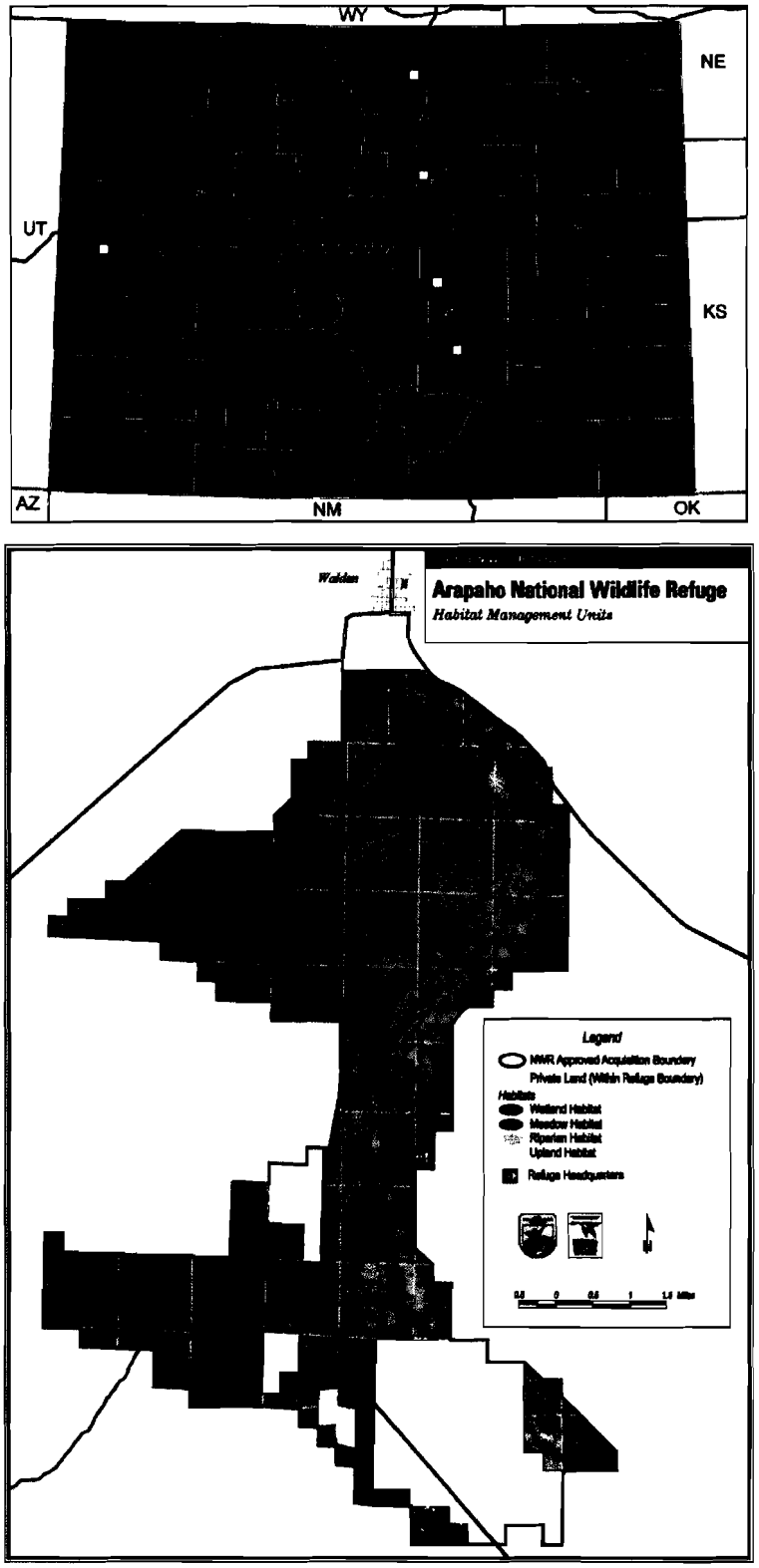

Figure 1. Locations of upland, meadow, and riparian habitats at Arapaho National Wildlife Refuge (NWR; bottom map) and location in northern Colorado (top map; two-letter labels represent standard U.S. state abbreviations). Map source is USFWS (2004).

canopy cover, <20% canopy cover of grasses, and >5% canopy cover of forbs.

Methods

Vegetation data were collected from 2005 to 2008 to monitor status and trends in the vegetation conditions required to meet the Refuge habitat management objectives. Vegetation data were obtained on 900 30-m transects located randomly with respect to all upland, meadow, and riparian acreage. Roads and water bodies were excluded from the sample area, and transect locations were restricted to be >60 m apart. The total sample size of n = 900 was based on preliminary power analyses (differences in means), indicating a reasonable sample size of n = 150 for each of two habitat types in three equal-sized geographic areas of ANWR. Universal Transverse Mercator coordinates of transect starting locations were recorded, and locations were marked in the field. Transect orientation was randomly selected. Transects were measured in logistically convenient geographic groupings in 2005 (n = 208), 2006 (n = 250), 2007(n = 258), and 2008 (n = 184).

Canopy cover of herbaceous and shrub vegetation on each transect were based on point intercepts of canopies at 100 equally spaced points along the 30-m transects. Heights of live vegetation at canopy hits were recorded to the nearest centimeter. Point intercepts with bare ground and duff also were recorded, and depths of duff to the nearest centimeter were recorded. The VORs were recorded to the nearest centimeter in four cardinal directions from a Robel pole (Robel et al. 1970) placed at the center of transects in riparian and meadow habitats. For the purposes of evaluating habitat management objectives at ANWR, the vegetation measures on each upland transect were summarized into proportion of the shrub canopy cover that was sagebrush, canopy cover of sagebrush ≥25 cm in height, canopy cover of sagebrush ≥40 cm in height, canopy cover of forbs, and canopy cover of grass. The vegetation measures on each meadow or riparian transect were summarized into proportion of the grass and forb canopy cover that was grass (grass : forb ratio), average depth of duff, percentage of bare ground, and average VOR.

We used quantiles ($\tau \in [0, 1]$, percentiles = 100% × τ) as the basis for our statistical analysis to evaluate the state of ANWR vegetation conditions because the habitat management objectives specify proportions of the total habitat area (e.g., 809 of 5,781 ha) that need to meet specified vegetation conditions (e.g., 20–30% canopy cover of sagebrush ≥25 cm in height). Quantiles, as the inverse of the cumulative distribution function, quantify the values associated with a distribution that have specified proportions of the distribution less than or equal to that value (Cade and Noon 2003) and are well suited for this type of analysis with appropriate sampling designs. An equivalence testing approach was used because our interest was in establishing whether estimated proportions (sample quantiles) of the monitoring data indicated the population proportions were within specified intervals of nonzero values (e.g., 20–30% canopy cover of sagebrush ≥25 cm in height) rather than differing from a single fixed value (e.g., 0% canopy cover). Furthermore, the equivalence testing framework allowed us to interpret sampling variability under two different forms of hypotheses (and associated confidence intervals): a null hypothesis of inequivalence and a null hypothesis of equivalence with respect to the equivalence region (McBride and Ellis 2001, Camp et al. 2008, Cade 2011).

When the null hypothesis of inequivalence is used, we minimize risk (type I error rate under H_0) of claiming that the population of vegetation conditions comply with the management objectives when that is not true. This is often termed minimizing "consumer" risk (McBride 1999, McBride and Ellis 2001, Manly 2004, Cade 2011). In the context of compliance with habitat objectives this can be thought of as a conservative, fail-safe interpretation where we have little doubt that the population proportions met the criteria. When the null hypothesis of equivalence is used, we minimize risk of claiming that the populations of vegetation conditions do not comply with the management objectives when that is not true. This is often termed minimizing "producer" risk (McBride 1999, Food and Drug Administration 2001, McBride and Ellis 2001, Cade 2011). In the context of compliance with habitat objectives, this can be thought of as a liberal, benefit-of-doubt interpretation where some evidence exists that the population proportions might have been met. The notion that the different hypotheses imply either a liberal or conservative interpretation of sampling variability is relevant when evaluating management objectives to assess future management activities. The liberal interpretation will always find greater area in compliance compared with the conservative interpretation of sampling variation. As sampling variation decreases with increasing sample size, the differences between compliance determined by the liberal, benefit-of-doubt and conservative, fail-safe procedures also decreases. Good introductions to the concepts of equivalence testing are provided by McBride et al. (1993) and Parkhurst (2001).

The theory of equivalence testing with its various null hypotheses (inequivalence or equivalence) that may be one- or two-sided hypotheses, depending on the management objectives, underlies our approach. Our actual implementation was facilitated by simple use of one-tailed or two-tailed confidence intervals on the quantile estimates (Cade 2011). This allowed us to evaluate what proportion of the population cumulative distribution function was within intervals of conditions prescribed by the management objectives accounting for the sampling variation of our quantile estimates (McBride and Ellis 2001, Cade 2011). In our analyses, one- and two-sided equivalence regions were defined by intervals of vegetation conditions specified for components of the habitat management objectives. One-sided equivalence regions were those where either minimum or maximum attainable values were not defined based on habitat management objectives but rather by the limits of the measurement scale. Most equivalence regions were straight-forward extensions of the habitat

management objectives, but the condition of a grass : forb ratio of 75:25 specified in management objectives 1A and 1B required interpreting management intent to specify a region in terms of intervals. We defined this component criterion as a one-sided equivalence region of ≤0.75 grass, i.e., grass : forb ratios ≤75:25, because the intent of this criterion was to ensure plant communities had a large component of forbs. Other equivalence regions for components of management objective 1A in meadow and riparian habitats were defined as 1–3 dm VOR (two-sided), ≤5% bare ground (one-sided), and ≤10-cm depth of duff (one-sided). Management objective 1B substituted equivalence regions for 10–20-cm depth of duff (two-sided) and ≥3 dm VOR (one-sided). Equivalence regions for components based on management objective 2A in upland habitats were defined as ≥0.70 sagebrush in the shrub canopy cover (one-sided), ≥10% forb canopy cover (one-sided), ≥20% grass cover (one-sided), and 20–30% canopy cover of sagebrush ≥25 cm in height (two-sided). Management objective 2B substituted ≥30% canopy cover of sagebrush ≥40 cm in height (one-sided), ≥5% forb canopy cover (one-sided), and ≤20% grass cover (one-sided).

We estimated quantiles in a linear quantile regression model (Cade and Noon 2003, Koenker 2005, Cade 2011) to obtain estimates for vegetation components that were averages across the 4 y sampled. Averages were used both because of considerable annual variation in vegetation conditions at ANWR, primarily associated with annual variation in precipitation, and because the habitat management objectives specified conditions to be met over multiple years. We considered our use of averages over 4 y as meeting the intent of the 5-y average specified in the CCP. The linear quantile regression model used was $Q_Y(\tau|\mathbf{X}) = \beta_0(\tau) + \beta_1(\tau)X_1 + \beta_2(\tau)X_2 + \beta_3(\tau)X_3$, where Y was a given vegetation variable; X_1, X_2, and X_3 were orthogonal contrast indicators taking the values (1, 0, 0) for 2005, (0, 1, 0) for 2006, (0, 0, 1) for 2007, and (−1, −1, −1) for 2008; and $\tau \in [0, 1]$. In this linear model parameterization, the intercept term $\beta_0(\tau)$ is the average across the 4 y for the τth quantile, and $\beta_1(\tau)$ to $\beta_3(\tau)$ are differences for individual years from the 4-y average (the fourth difference obtained by subtraction). We obtained estimates for 5th to 95th percentiles (τ = 0.05–0.95 by increments of 0.01) and their confidence intervals for $\beta_0(\tau)$ based on rank score test inversion (Koenker 2005, Cade et al. 2006). Rank score–based confidence intervals are reliable for these moderate-sized samples (Cade et al. 2006). We graphed quantile estimates and confidence intervals across 5th to 95th percentiles to determine the proportion of the 4-y averages satisfying the equivalence regions defined by the habitat management objectives. We randomly jittered raw values by adding a random uniform number an order of magnitude smaller than raw data values when graphing confidence intervals to minimize convergence issues with the rank score test procedure associated with many tied values. However, our actual determination of quantiles satisfying the equivalence regions was based on rank score confidence intervals on the raw data. One-tailed 95% confidence intervals were used to evaluate one-sided equivalence regions corresponding to an α = 0.05 one-sided equivalence test and were obtained by using the appropriate tail of two-tailed 90% confidence intervals (α = 0.05 in one tail). Two-tailed 90% confidence intervals were used to evaluate two-sided equivalence regions corresponding to two one-sided equivalence tests at an α = 0.05 (Cade 2011). Code to implement the quantile regression analyses and graph the estimates using the "quantreg" package in R (R Development Core Team 2011) is provided in Appendix S1 (*Supplemental Material*; http://dx.doi.org/10.3996/052011-JFWM-032.S1). All transect data used in analyses are provided in Data S1(*Supplemental Material*; http://dx.doi.org/10.3996/052011-JFWM-032.S2).

We evaluated the proportion of the sample in the habitat types satisfying criteria for multiple vegetation components simultaneously because the habitat management objectives imply that combinations of the vegetation conditions need to be met on the same area. This was done by determining the proportion of the habitat transects that met the quantile equivalence simultaneously for all vegetation conditions specified. We subsetted the entire sample for a habitat type by those transects that had values within the interval of quantiles that met criteria for each vegetation component by year using Boolean conditional statements. The proportions of transects that met all quantile equivalences simultaneously by year were then averaged across years to obtain an overall estimate of the proportion in compliance. This procedure implies that the combination of vegetation conditions needs to be met at a small spatial scale (within a 30-m transect) to fulfill habitat management objectives. This seemed reasonable for the herbaceous conditions being evaluated in the meadow and riparian habitats. It was perhaps a less reasonable assumption for the upland habitats where combinations of sagebrush and herbaceous vegetation conditions were being evaluated. Higher herbaceous cover does not occur where shrub cover also is high due to competitive exclusion. Therefore, we also considered assigning transects as having met the combination of component criteria for management objectives in the upland habitat if the quantiles of the sagebrush and the quantiles of the grass and forb components were met on separate transects within specified distances of each other. We considered a range of reasonable distances between 100 and 1,200 m to examine the consequences of this choice on compliance with management objectives. Note that 0.0 distances represent instances when the component criteria were met on the same transect (<30-m distance). Euclidean distances between transects based on the Universal Transverse Mercator northing and easting coordinates were computed using distance functions from the "fields" package in R (R Development Core Team 2011).

Results

Meadow and riparian habitat

The meadow and riparian habitats had the same management objectives with respect to vegetation

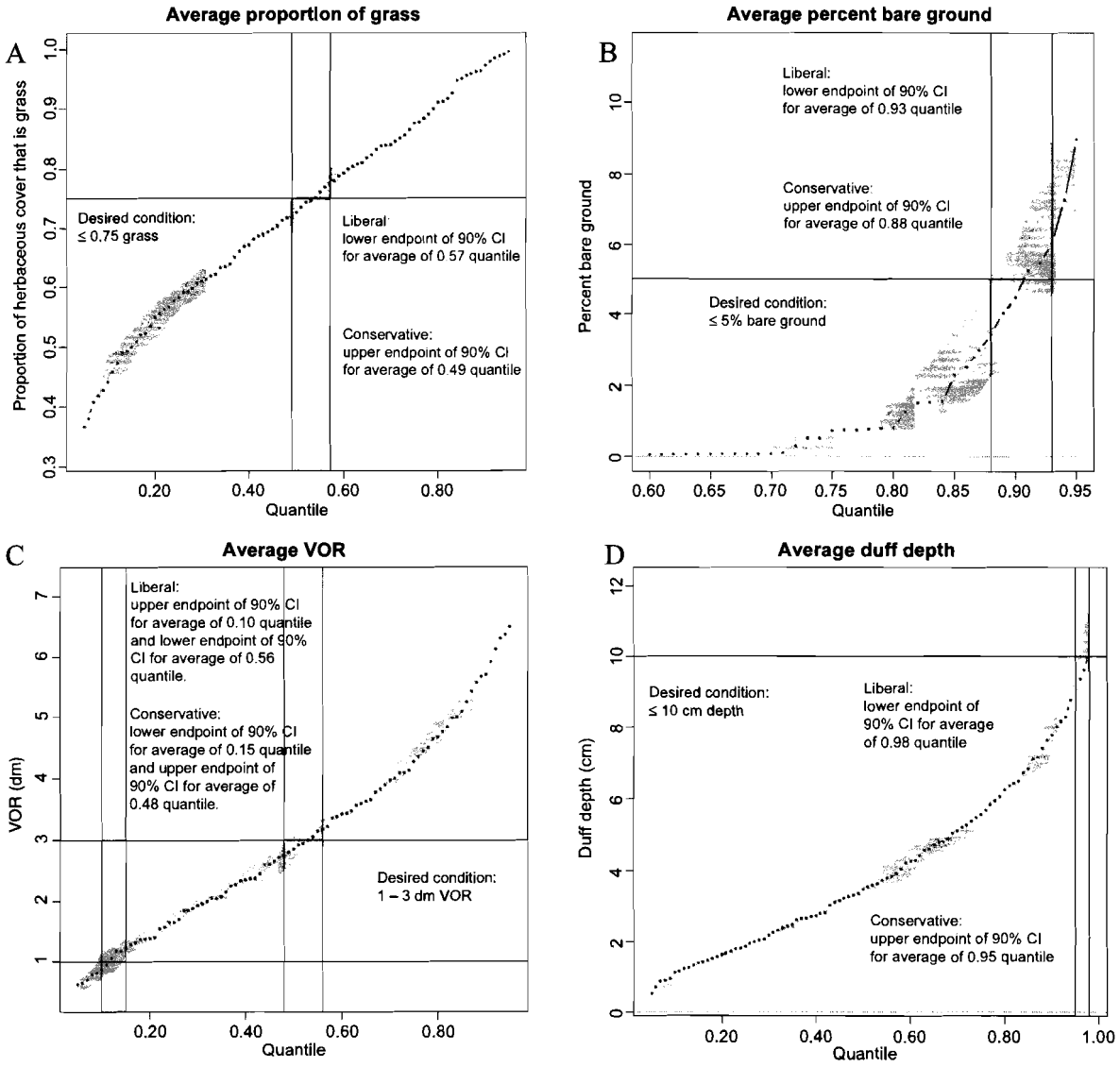

Figure 2. Meadow and riparian habitat at Arapaho National Wildlife Refuge. Proportion of the herbaceous cover that is grass (**A**), percentage of bare ground (**B**), visual obstruction reading (VOR) in decimeters (**C**), and duff depth in centimeters (**D**) for quantiles (**A** and **C**, 0.05–0.95; **B**, 0.60–0.95; **D**, 0.05–0.98 by increments of 0.01) averaged across 2005–2008; quantile estimates are small black points and gray bands connect 90% confidence intervals (CIs); n = 389 transects (**C**; n = 378). Blue vertical lines bound quantiles where 90% CIs (α = 0.05 for single one-sided tests and α = 0.05 for two one-sided tests) for averages across the 4 y overlap with the equivalence region of desired conditions under the liberal, benefit-of-doubt interpretation of sampling variation. Red vertical lines bound quantiles where 90% CIs for averages across the 4 y are contained within the equivalence region of desired conditions under the conservative, fail-safe interpretation of sampling variation.

measures, except that riparian habitat had a restriction of ≤40% canopy cover of willows. The maximum canopy cover of willows in any year was 34%, and the 90th percentiles were 0% in all years. Thus, this condition was deemed met across virtually all acreage of riparian habitat. We, therefore, analyzed the other vegetation components of riparian and meadow habitats together. The maximum proportion of nonnative, invasive plants recorded was 0.09, and 90th percentiles were all <0.02 in any year, indicating dominance of native plant communities. Annual cumulative distributions of each variable are shown in the Figures S1–S4 (*Supplemental Material*; http://dx.doi.org/10.3996/052011-JFWM-032.S3) and indicate minor variation among years in proportion of cover that is grass and percentage of bare ground but more substantial annual variation in depth of duff and VOR.

Based on a liberal (null hypothesis of equivalence) interpretation of sampling variation, 57% of the meadow and riparian habitat type met the specified condition of ≤0.75 average proportion grass (Figure 2A), 93% met the condition of ≤5% average bare ground (Figure 2B), 47% [0.47 = 1.0 − (0.10 − 0.01) − (1.0 − 0.56)] met the condition of 1–3-dm average VOR (Figure 2C), and 98%

Table 1. Estimates of hectares (acres in parentheses) complying with vegetation conditions for habitat management objectives 1A and 1B for meadow and riparian habitat (total area = 2,856 ha [7,057 acres]) at Arapaho National Wildlife Refuge based on quantile equivalence analyses for averages across 2005–2008 (total area × corresponding proportion), and area desired to meet objectives. Liberal estimates are based on 90% confidence intervals associated with null hypotheses of equivalence and conservative estimates are based on 90% confidence intervals associated with null hypotheses of inequivalence.

Vegetation condition	Liberal estimate	Conservative estimate
1A: 2,137–2,305 ha (5,280–5,695 acres) desired		
Proportion grass ≤0.75	1,628 (4,022)	1,399 (3,458)
Bare ground ≤5%	2,656 (6,563)	2,513 (6,210)
VOR[a] 1–3 dm	1,342 (3,317)	971 (2,399)
Duff depth ≤10 cm	2,799 (6,916)	2,713 (6,704)
All four conditions simultaneously	717 (1,771)	405 (1,000)
1B: 340–492 ha (840–1,215 acres) desired		
Proportion grass ≤0.75	1,628 (4,022)	1,399 (3,458)
Bare ground ≤5%	2,656 (6,563)	2,513 (6,210)
VOR ≥3 dm	1,485 (3,670)	1,257 (3,105)
Duff depth 10–20 cm	143 (353)	0 (0)
All four conditions simultaneously	54 (134)	0 (0)

[a] VOR = visual obstruction reading.

met the condition of ≤10-cm average duff depth (Figure 2D). The areas of meadow and riparian habitat corresponding to these proportions are shown in Table 1. There were 99 of the 389 sample transects that met all combination of conditions for the components, with an average proportion across years of 0.2509, equating to 717 of 2,856 ha of all meadow and riparian habitats that might have met all conditions of the objective on the same transect. The locations of transects meeting all component conditions are shown in Figure 3.

In contrast, based on a conservative (null hypothesis of inequivalence) interpretation of sampling variation, 49% of the meadow and riparian acreage met the desired condition of ≤0.75 average proportion grass (Figure 2A), 88% met the condition of ≤5% average bare ground (Figure 2B), 34% [0.34 = 1.0 − (0.15 − 0.01) − (1.0 − 0.48)] met the condition of 1–3-dm average VOR (Figure 2C), and 95% met the condition of ≤10-cm average duff depth (Figure 2D). The areas of meadow and riparian habitat corresponding to these proportions are in Table 1. Of the 389 transects in these habitat types, 56 met all the component conditions specified in the objective, yielding an average proportion of 0.1417, equating to 405 ha of the meadow and riparian habitat that almost surely met the combination of conditions specified in the objectives on the same transect.

Regardless of our interpretation (liberal or conservative) of the sampling variation in the monitoring data, the area that met all conditions in objective 1A was less than the objective of 2,137 to 2,305 ha (Table 1). Although the proportion of meadow and riparian habitat with ≤5% bare ground and ≤10-cm depth of duff were sufficiently abundant in proximity to satisfy the objective, too much of the area has >3 dm VOR and >0.75 grass (grass : forb ratio exceeding 75:25; Table 1). The location of sample transects satisfying the VOR or proportion grass cover component criteria separately are shown in Figures S5 and S6 (*Supplemental Material*; http://dx.doi.org/10.3996/052011-JFWM-032.S3).

Management objective 1B for meadow and riparian habitats differs from objective 1A by requiring VOR ≥3 dm and 10–20-cm duff depth. Figure 2D indicates 5% of the meadow and riparian habitat met the 10–20-cm duff depth criteria under the liberal interpretation of sampling variation, but none of the area met this criterion under the conservative interpretation. For VOR ≥3 dm, 52% [0.52 = 1.0 − (0.49 − 0.01)] of the habitat met the objective using the liberal interpretation of sampling variation, whereas 44% [0.44 = 1.0 − (0.57 − 0.01)] met the objective using the conservative interpretation (Figure 4A). There were only 8 of the 389 transects that satisfied all component criteria specified in objective 1B under the liberal interpretation of sampling variation with an average proportion of 0.0189, indicating 54 ha of the riparian and meadow habitat might have met this objective. In contrast, no transects satisfied all component criteria of the objective using the conservative interpretation of sampling variation. Regardless of which interpretation of sampling variation was used, lack of sufficient area with duff depths >10 cm was the issue for compliance with objective 1B (Table 1).

Upland habitat

Based on a liberal interpretation of the sample variation relative to management objective 2A, 60% [0.60 = 1.0 − (0.41 − 0.01)] of the upland habitat had an average proportion of sagebrush ≥0.70 (Figure 5A). Similarly, 21% [0.21 = 1.0 − (0.80 − 0.01)] had ≥10% average forb canopy cover (Figure 5B), 67% [0.67 = 1.0 − (0.34 − 0.01)] had ≥20% average grass canopy cover (Figure 5C), and 19% [0.19 = 1.0 − (0.82 − 0.01)] had an average canopy cover of 20–30% for sagebrush ≥25 cm in height (Figure 5D). Areas corresponding to these

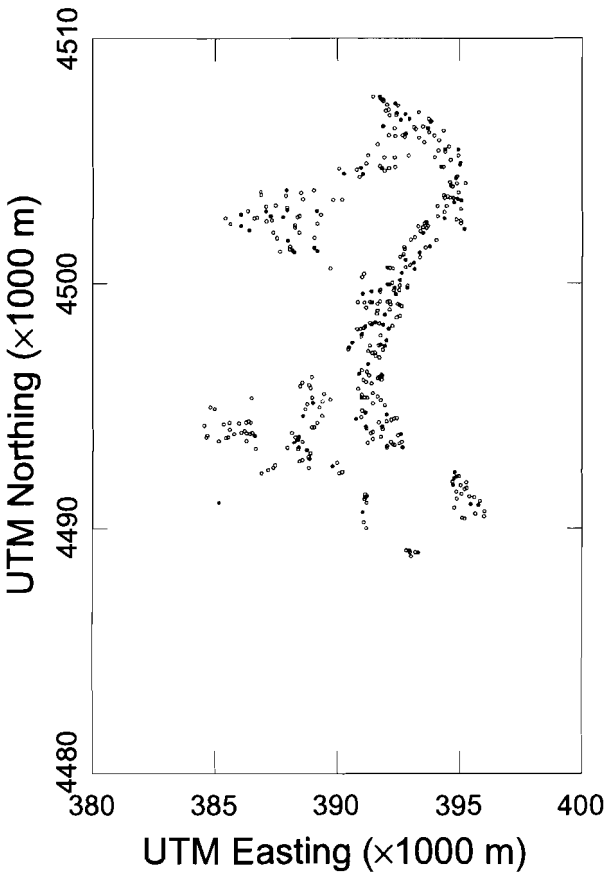

Figure 3. Locations of 389 meadow and riparian sample transects in geographic space at Arapaho National Wildlife Refuge. UTM = Universal Transverse Mercator coordinates. Size of circles is approximately 200 m in diameter. Solid red circles (n = 99) denote those sample transects that simultaneously met the average (2005–2008) quantiles for equivalence for bare ground, duff depth, proportion grass, and visual obstruction readings under the liberal, benefit-of-doubt criteria.

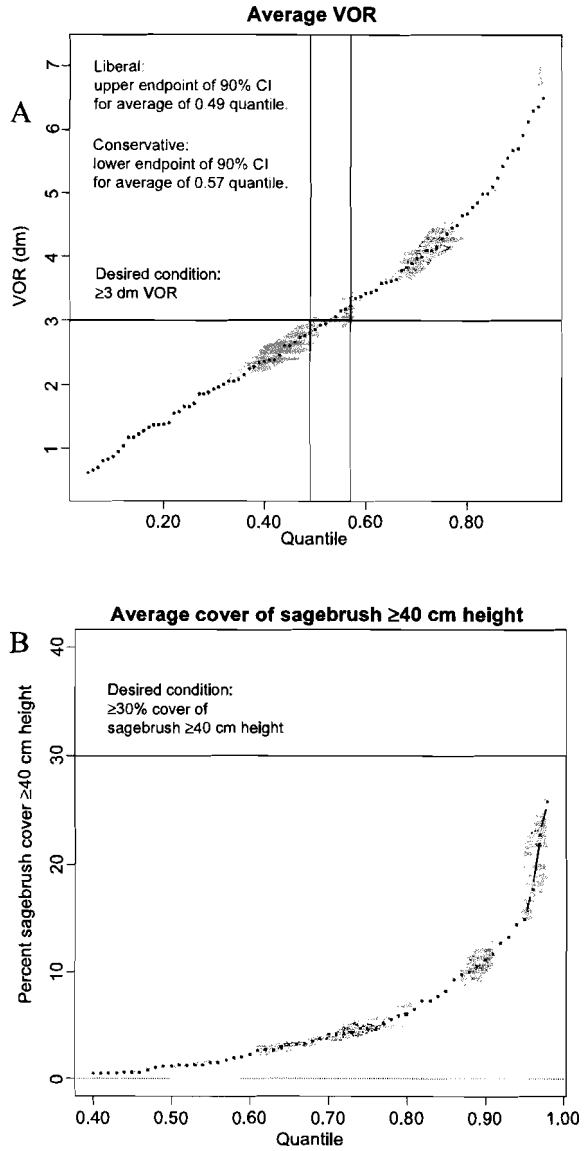

Figure 4. (**A**) Meadow and riparian habitat at Arapaho National Wildlife Refuge. Visual obstruction (VOR) reading in decimeters for quantiles (0.05–0.95 by increments of 0.01) averaged across 2005–2008; n = 378 transects; quantile estimates are small black points and gray band connects 90% confidence intervals (CIs). Blue vertical line bounds quantiles where 90% CIs for the average across years overlap with the desired condition of ≥3-dm VOR under a liberal interpretation of sampling variation. Red vertical line bounds quantiles where 90% CIs for the average across years are contained within the desired condition of ≥3-dm VOR under a conservative interpretation of sampling variation. (**B**) Upland habitat. Cover of sagebrush (*Artemisia* spp.) ≥40 cm in height for quantiles (0.40–0.98 by increments of 0.01) averaged across 2005–2008; n = 511 transects. There was no evidence under either the liberal, benefit-of-doubt or conservative, fail-safe approaches that any of the quantiles ≤0.98 satisfied the desired management condition of ≥30% canopy cover.

proportions are in Table 2. Only 16 of the 511 sample transects met all component criteria specified in objective 2A, with an average proportion across years of 0.0311, equating to 180 ha of the 5,781-ha total upland habitat area that might have met the combination of conditions on the same transect (Table 2). However, if we allowed transects that met the sagebrush cover or grass and forb cover within specified distances of each other to count toward satisfying objective 2A, the proportion of the sample that met the combination of conditions increased substantially (Figure 6): 0.0472 (273 ha) at 100 m, 0.2957 (1,710 ha) at 600 m, and up to 0.3687 (2,132 ha) at 1,200 m. The locations of transects that met all component conditions simultaneously, and locations of transects that met the component conditions within 200 m of each other (436 ha = 0.0755 × 5,781 ha]) are shown in Figure 7. Annual cumulative distributions of each variable are shown in the Figures S7–S11 (*Supplemental Material*; http://dx.doi.org/10.3996/052011-JFWM-032.S3) and indicate minor variation

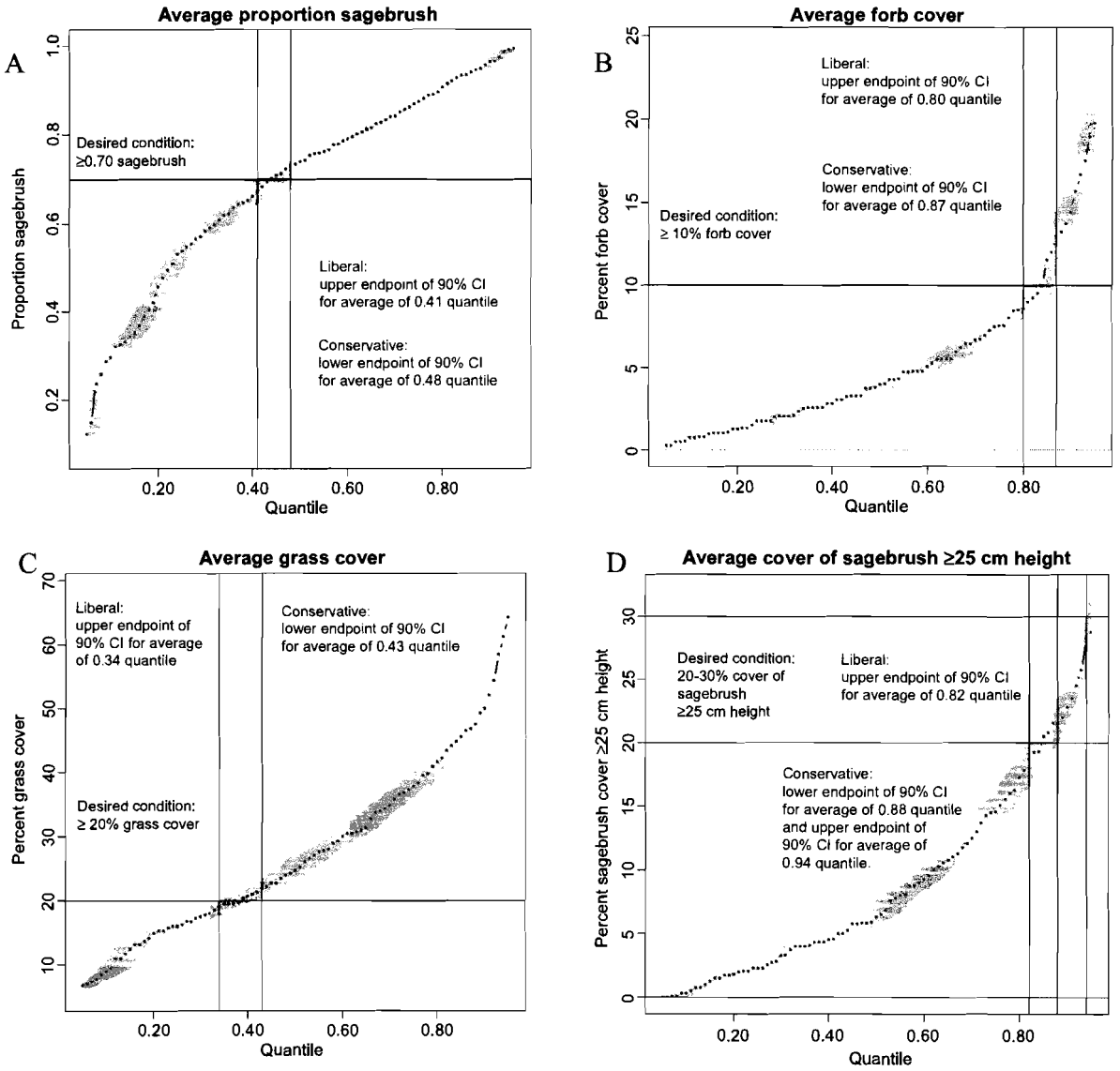

Figure 5. Upland habitat at Arapaho National Wildlife Refuge. Proportion of shrubs that were sagebrush (*Artemisia* spp; **A**), percentage of forb cover (**B**), percentage of grass cover (**C**), and percentage of cover of sagebrush ≥25 cm in height (**D**) for quantiles (0.05–0.95 by increments of 0.01) averaged across 2005–2008; quantile estimates are small black points and gray bands connect 90% confidence intervals (CIs); n = 511 transects. Blue vertical lines bound quantiles where 90% CIs (for α = 0.05 for single one-sided tests and α = 0.05 for two one-sided tests) for averages across the 4 y overlap with the equivalence region of desired conditions under the liberal, benefit-of-doubt interpretation of sampling variation. Red vertical lines bound quantiles where 90% CIs for averages across the 4 y are contained within the equivalence region of desired conditions under the conservative, fail-safe interpretation of sampling variation.

among years in sagebrush cover but substantial variation in grass and forb cover.

In contrast, a conservative interpretation of the sample variation in the upland habitat indicates 53% [0.53 = 1.0 − (0.48 − 0.01)] of the area had a 4-y average ≥0.70 sagebrush (Figure 5A), 14% [0.14 = 1.0 − (0.87− 0.01)] had ≥10% average forb canopy cover (Figure 5B), 58% [0.58 = 1.0 − (0.43− 0.01)] had ≥20% average grass canopy cover (Figure 5C), and 7% [0.07 = 1 − (0.88 − 0.01) − (1 − 0.94)] had 20–30% average canopy cover of sagebrush ≥25 cm in height (Figure 5D). Areas corresponding to these proportions are in Table 2. Only eight transects met all component criteria, with an average proportion of 0.0157, equating to 91 ha meeting the conditions specified in objective 2A (Table 2). However, if we allowed transects that satisfied the sagebrush cover or grass and forb cover within specified distances of each other to count toward satisfying objective 2A, the proportion of the sample that met the component conditions increased (Figure 6) from 0.0253 (146 ha) at 100 m to 0.1690 (977 ha) at 1,200 m.

Our analyses indicated that the proportion of upland habitat with ≥0.70 shrubs as sagebrush and ≥20% canopy cover of grass was sufficiently abundant in close

Table 2. Estimates of hectares (acres in parentheses) complying with vegetation conditions for habitat management objectives 2A and 2B for upland habitat (total area = 5,781 ha [14,285 acres]) at Arapaho National Wildlife Refuge based on quantile equivalence analyses for averages across 2005–2008 (total area × corresponding proportion), and area desired to meet objectives. Liberal estimates are based on 90% confidence intervals associated with null hypotheses of equivalence and conservative estimates are based on 90% confidence intervals associated with null hypotheses of inequivalence.

Vegetation condition	Liberal estimate	Conservative estimate
2A: 809 ha (2,000 acres) desired		
Proportion sagebrush ≥0.70	3,469 (8,571)	3,064 (7,571)
Forb canopy cover ≥10%	1,214 (3,000)	809 (2,000)
Grass canopy cover ≥20%	3,873 (9,571)	3,353 (8,285)
20–30% canopy cover sagebrush ≥25 cm height	1,098 (2,714)	405 (1,000)
All four conditions simultaneously	180 (444)	91 (225)
2B: 809 ha (2,000 acres) desired		
Proportion sagebrush ≥0.70	3,469 (8,571)	3,064 (7,571)
Forb canopy cover ≥5%	2,544 (6,285)	2,081 (5,143)
Grass canopy cover ≤20%	2,428 (6,000)	1,908 (4,714)
≥30% canopy cover sagebrush ≥40 cm in height	0 (0)	0 (0)
All four conditions simultaneously	0 (0)	0 (0)

proximity, i.e., within a 30-m transect, to meet management objective 2A. In contrast, the area with a combination of 20–30% sagebrush cover and ≥10% forb cover at this spatial scale was insufficient to meet the management objective. This was supported by evaluating the location of sample transects satisfying the sagebrush canopy cover or forb canopy cover criteria separately (*Supplemental Material*, Figures S12 and S13; http://dx.doi.org/10.3996/052011-JFWM-032.S3) and by the increasing area of upland habitat satisfying all component criteria in objective 2A as permissible distances between transects that met the sagebrush cover and composition and transects that met the grass and forb components increased under both the liberal and conservative interpretations of sampling variation (Figure 6).

One of the habitat conditions specified in upland objective 2B required ≥30% canopy cover of sagebrush ≥40 cm in height. This requirement was not met on upland habitat, regardless of how we interpreted sampling variation (Table 2). Even under the liberal interpretation of sampling variation, the confidence intervals for all quantiles ≤0.98 indicated the canopy cover of sagebrush ≥40 cm in height was substantially less than the required 30% for objective 2B (Figure 4B). It is possible that confidence intervals for the upper two percentiles (quantiles ≥0.99) might have included 30% canopy cover if they could have been estimated reliably, but this would have indicated that a maximum of 0.02 of the upland area (116 ha) would have met this objective.

Discussion

The quantile equivalence analyses provided a strong indication of which individual vegetation criteria were more or less likely to be out of compliance with the specified management objectives. For management objective 1A in the meadow and riparian habitat that requires 2,137–2,305 ha under the desired conditions, the criteria for ≤5% bare ground and a ≤10-cm depth of duff components were readily met on >2,428 ha with either a liberal or conservative interpretation of the sampling variation of the estimates. There was insufficient area with 1–3-dm VOR (971–1,342 ha) and ≤75:25 grass : forb ratio (1,399–1,628 ha) under either interpretation of sampling variation. Because management objective 1B requires only 340–492 ha of meadow and riparian habitat with ≥3-dm VOR and there were 1,257–1,485 ha in this condition, converting a portion of this higher VOR area to the lower VOR conditions is required to comply with objective 1A. The depths of duff were well below the 10–20-cm range required to satisfy management objective 1B that requires 12% (340 ÷ 2,856 ha) of the area to have duff depths in this interval. Serious consideration should be given to evaluating whether this duff depth criterion for management objective 1B really is ecologically reasonable at ANWR based on annual vegetation productivity. A reduction in the grass : forb ratio by increasing relative amount of forb cover on >405 ha also is required to comply with both objectives 1A and 1B for the meadow and riparian habitats.

The pattern of grass : forb ratios (Figure 2) can be used to demonstrate the utility of the quantile equivalence analyses for evaluating sensitivity of criteria specification for management objectives. The current deficiency of >405 ha of riparian and meadow habitat was based on grass : forb ratios ≤75:25. However, if the acceptable ratio was increased to ≤85:15, allowing up to 0.10 more grass, then 1,913–2,143 ha (conservative to liberal interpretations of sampling variation, respectively) would have met this criterion for objective 1A. This can be visualized by simply sliding up the horizontal line in Figure 2A to intercept 0.85 and then examining where

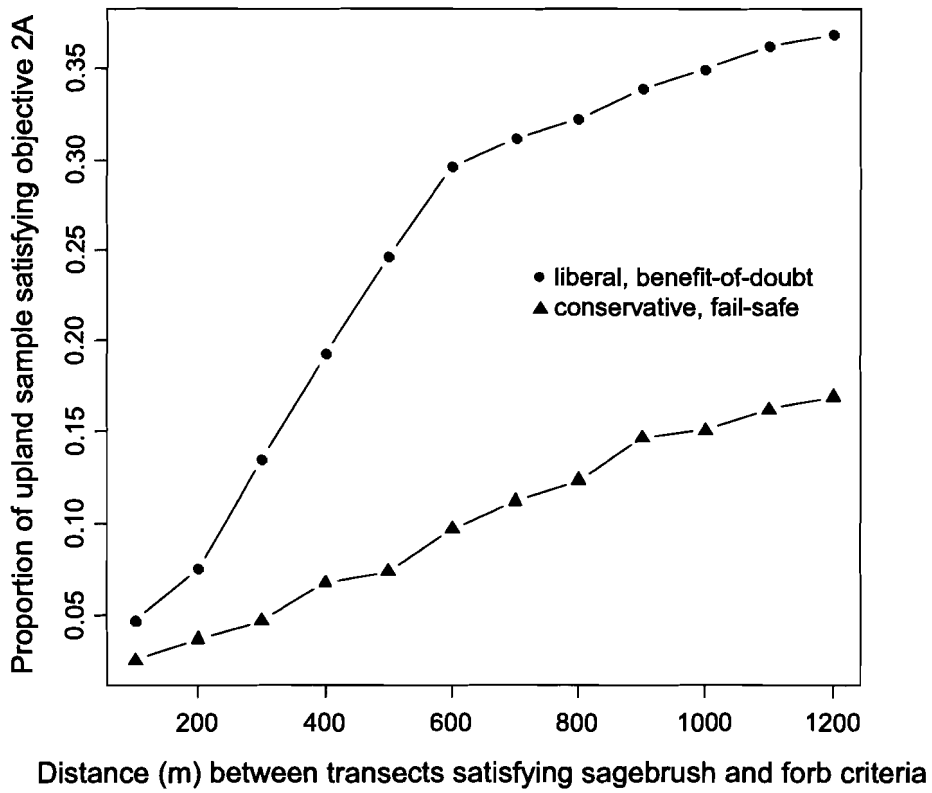

Figure 6. Upland habitat at Arapaho National Wildlife Refuge. Proportion of n = 511 transects that satisfied average quantiles across 2005–2008 for proportion sagebrush (*Artemisia* spp.) and canopy cover of sagebrush ≥25 cm in height and grass canopy cover and forb canopy cover within specified distances of each other under the liberal, benefit-of-doubt (circles) and conservative, fail-safe approaches (triangles) to considering sampling variation. Note that 0.14 of the total 5,781 ha is required to satisfy the 809-ha requirement of management objective 2A.

the confidence intervals of the quantile estimates intercept this value by projecting vertical lines. Conversely, if the grass : forb ratio was reduced to ≤65:35 (0.10 less grass), sliding down the horizontal line in Figure 2A to intercept 0.65 and then examining where the confidence intervals of the quantile estimates intercept this value would establish how much less habitat met this criterion specification. To the extent that the specification of grass : forb ratios ≤75:25 was fuzzy as a management objective, having been based on a synthesis of a variety of ecological literature (USFWS 2004), we can examine the impact of considering alternative criteria (e.g., allowing up to 0.10 more or less grass) as acceptable management objectives. If the evidence in the scientific literature is ambiguous about whether a grass : forb ratio as high as 85:15 is acceptable for the wildlife habitat desired, then this slight change in specification of criteria would place ANWR closer to being in compliance with the intent of management objective 1A. In this context, analysis of the monitoring data can serve as feedback to help evaluate the sensitivity of habitat management objectives to details of the numerical specification of criteria. We are not, however, suggesting that all criteria should be altered simply to make it look as if compliance was achieved. Rather, we are suggesting that such an assessment is warranted to the extent that some criteria for habitat management objectives have greater uncertainty in their specification.

There was some deficiency in area of upland habitat at ANWR with 20–30% canopy cover of sagebrush ≥25 cm in height and ≥10% canopy cover of forbs to satisfy management objective 2A that requires 809 ha of these conditions. Although there was 809–1,214 ha (conservative to liberal interpretations, respectively) with ≥10% canopy cover of forbs and 405–1,098 ha with 20–30% canopy cover of sagebrush ≥25 cm in height, there was minimal overlap of these component conditions (91–180 ha) at the scale of a 30-m transect. Our analyses indicated that if distances between the upland areas that met the forb and grass conditions and those that met the sagebrush conditions were allowed to be slightly greater than 300 m to be considered acceptable, then management objective 2A would be satisfied under the liberal interpretation of sampling variation. However, even extending distances to 1,200 m would still indicate a deficiency of upland area satisfying these conditions under the conservative interpretation of sampling variation. Therefore, ANWR may want to consider whether there is an acceptable distance >100 m between upland habitat meeting herbaceous criteria and those meeting sagebrush criteria but also increase the area with 20–30% canopy cover of sagebrush ≥25 cm

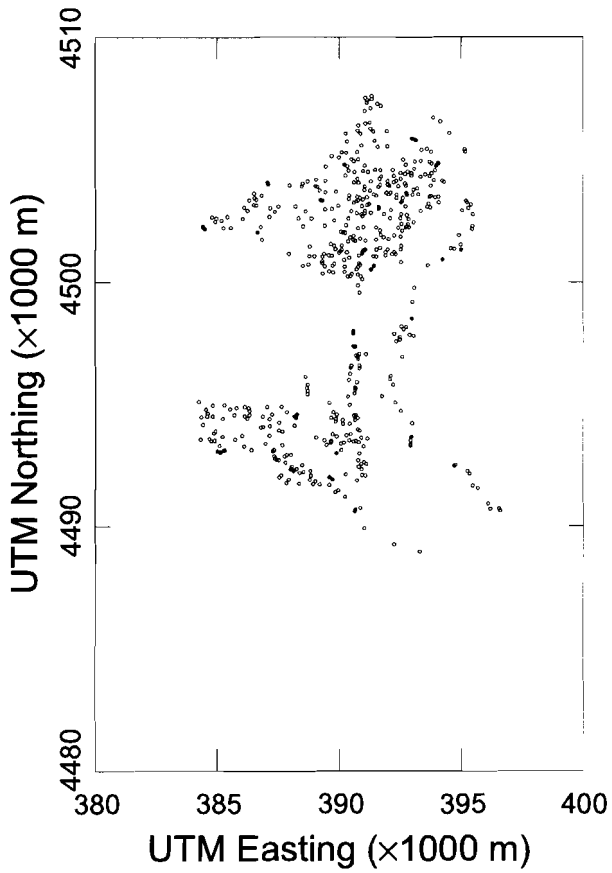

Figure 7. Locations of 511 upland sample transects in geographic space at Arapaho National Wildlife Refuge. Size of circles is approximately 200 m in diameter. Solid red circles (n = 16) denote those sample transects that simultaneously met the average (2005–2008) quantiles for equivalence for sagebrush (*Artemisia* spp.) canopy cover, proportion sagebrush, grass cover, and forb cover under the liberal, benefit-of-doubt criteria. Solid black circles (n = 22) are those additional sample transects that met the vegetation conditions within 200-m distance of each other. UTM = Universal Transverse Mercator coordinates.

in height and ≥10% canopy cover of forbs. It also is worth noting that the two-sided equivalence region of 20–30% canopy cover of sagebrush ≥25 cm in height will inherently be more difficult to satisfy under the conservative interpretation of sampling variation because the two-tailed confidence intervals for the estimates have to be contained within fairly narrow constraints. Because there seems to be little area with >30% canopy cover of sagebrush, a reasonable alternative formulation of this objective might be to specify the component criterion as ≥20% canopy cover of sagebrush ≥25 cm in height, provided there were no serious concerns that areas with >30% canopy cover were detrimental and likely to be abundant. The corresponding equivalence region of ≥20% canopy cover of sagebrush ≥25 cm in height would now be one-sided and greater area would be in compliance with this revised objective. For all practical purposes, ANWR was completely deficient in upland area with ≥30% canopy cover of sagebrush ≥40 cm in height to meet the required 809 ha for management objective 2B. An investigation into site potential and evaluation of sagebrush canopy cover and heights in adjacent regions of North Park could help establish whether this objective is reasonable for ANWR.

There was substantial annual variation in the herbaceous vegetation in the upland habitats that was consistent with the annual variation in precipitation. Forb and grass cover were substantially lower at upland transects sampled in 2005 and 2006 compared with those transects sampled in 2007 and 2008. Precipitation from January to June was less in 2005 and 2006 compared with that in 2007 and 2008. The proportion of sagebrush cover and canopy cover of sagebrush in the uplands varied less among years. However, in the meadow and riparian habitats, VORs for herbaceous vegetation were greater in 2005 and 2006 compared with VORs in 2007 and 2008, although January-to-June precipitation was considerably less in 2005 and 2006 than in the later years. We might expect herbaceous vegetation in the meadow and riparian habitats to be less directly influenced by local precipitation differences than the upland habitats due to greater dependence on water from mountain snow delivered by the rivers. However, an alternative explanation is that the spatial arrangement of sampling within years was clustered in a fashion that confounded annual differences with spatial locations. Much of the meadow and riparian habitat sampled in 2005 and 2006 was concentrated in the lower elevations of the Illinois River floodplain, an area likely to be wetter in most years.

Our analyses of averages across years for the quantiles of the vegetation variables require that locations sampled in each year ideally are random samples in space. Otherwise, annual variation is confounded with spatial variation. The initial sample locations at ANWR were obtained randomly in space. However, the actual implementation of the sampling plan at ANWR had personnel sample locations in logistically convenient spatial arrangements within a year, eliminating the random selection mechanism as a logical basis for making a link between the sample and the population of vegetation conditions. Logistically feasible sampling plans that compromise the ideal statistical design will often be used to implement extensive vegetation monitoring plans similar to that at ANWR. However, it is possible to reduce the confounding of space and time by devoting more attention to spreading the sampling in space each year, even if it is less than the ideal of random allocation of spatial locations each year. For example, alternatives being considered at ANWR are to randomly sample Refuge defined management areas (fields) each year, spreading the sample in space, but to measure all transects located within the area the year it is selected to make this plan logistically practical. Repeating these quantile equivalence analyses for future 4-y intervals will allow ANWR to track how compliance with the management objectives changes over time due to natural processes and habitat management.

In our analyses we used averages across quantiles that were not weighted by relative sample size because we wanted each year to contribute equally to the average regardless of differences in sample sizes among years. However, in other applications it might be desirable to use weighted average quantile estimates (e.g., weights proportional to relative sample size). It is simple to incorporate weights in a linear quantile regression model as is done in other linear models (Koenker 2005).

Our application of quantile equivalence analyses required the use of a linear model via quantile regression because of our desire to average across years when determining proportions of total acreage satisfying habitat management objectives. It is quite feasible to extend our approach to simpler one-sample designs that have no need for linear model estimates. Confidence intervals on one-sample quantile estimates can be obtained for equivalence analyses based on use of the binomial distribution as explained in McBride and Ellis (2001). Establishing equivalence to evaluate compliance for habitat management objectives that have criteria specified for total quantities on specified areas (e.g., total vegetation biomass) can be conducted by using confidence intervals on estimates of means in one-sample designs or for estimates of means in a linear model for more complex designs (McBride 1999, Parkhurst 2001, Limentani et al. 2005).

The joint evaluation of multiple vegetation criteria for compliance with management objectives using our approach modifies straight-forward Boolean conditional arguments for determining the proportion of a multivariate sample that simultaneously satisfy conditions on the multiple vegetation components to reflect the sampling variation of quantiles for the individual vegetation variables. A joint confidence region for the multiple variables was not specified but would certainly not have the same $(1 - \alpha)100\%$ confidence level as the individual 95% confidence intervals used. We know based on the Šidák (1967) inequality that with $k = 4$ univariate components normally distributed (sampling distributions of quantile regression estimates converge to this asymptotically) with individual $95\% = (1 - \alpha)100\%$ confidence levels that $81.5\% = (1 - (1 - (1 - \alpha)^k))100\%$ is a lower bound on the joint confidence level for the multivariate normal distribution assuming independent components (Westfall and Young 1993, 45–46). The actual joint confidence level would be between 81.5 and 95% depending on the correlation among the four variables. One could use individual $(1 - (1 - (1 - \alpha)^{1/k}))100\%$ confidence levels for the k components to ensure a simultaneous joint interval of $(1 - \alpha)100\%$ confidence level (e.g., 98.7% with $k = 4$ individual intervals for a simultaneous joint interval of 95%), a conservative approach, or perhaps obtain less conservative levels with some appropriately structured resampling approach (Westfall and Young 1993). However, it is not obvious whether a joint confidence level as proposed here could be used to estimate a joint confidence interval for the joint proportion because this proportion was based on different parameters (quantiles) for different variables with both one- and two-tailed confidence intervals. This remains an open research question. We note that an advantage of our evaluation of multiple univariate equivalences based on distances among sample units (transects in our case) is that even though the joint proportion determined is dependent on the covariation among the vegetation variables, we do not need to assume or estimate a particular covariance structure among the variables, and the effect of any covariation is not limited to the scale of the sample units (30-m transects in our case) as would be the case for a multivariate estimate.

Quantile equivalence analyses provide a valuable tool for land managers to evaluate the current state of portions of their habitats with respect to management objectives. Certainty of the determinations is increased when there is less difference between liberal and conservative interpretations of the sampling variability of estimates. Incorporating the sampling variation of estimates for individual components of a multivariate objective permits us to evaluate consequences of the numerical specification of interval objectives that might not have been recognized a priori when synthesizing ecological relationships lacking well defined linkages. Thus, a quantile equivalence analysis can serve to help managers refine how they specify their habitat management objectives in terms of intervals of acceptable values, as well as indicating components of objectives that are more or less well met, providing important inputs for adaptive management.

Supplemental Material

Please note: The *Journal of Fish and Wildlife Management* is not responsible for the content or functionality of any supplemental material. Queries should be directed to the corresponding author for the article.

Appendix S1. Code used to implement the quantile equivalence analyses with the "quantreg" and "fields" packages for R (R Development Core Team 2011).

Found at DOI: http://dx.doi.org/10.3996/052011-JFWM-032.S1 (87 KB RTF).

Data S1. Arapaho National Wildlife Refuge habitat data.

Found at DOI: http://dx.doi.org/10.3996/052011-JFWM-032.S2 (765 KB XLS).

Figures S1–S13. Sample statistics for vegetation variables by years and additional geographic locations for components of objectives that are in compliance based on quantile equivalence.

Found at DOI: http://dx.doi.org/10.3996/052011-JFWM-032.S3 (1891 KB DOC).

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