Federal, state, and private entities manage seasonal flooded, shallow wetlands to provide food and other habitat resources for wetland-dependent migratory birds, including migrating and wintering waterfowl. Individual National Wildlife Refuges managed by the U.S. Fish and Wildlife Service annually monitor seed production in moist-soil wetlands to track performance relative to regional foraging habitat objectives and to evaluate local habitat management activities. The National Wildlife Refuge System does not currently have a standard sampling protocol, and thus seeks a reliable rapid assessment method for estimating seed production to achieve standardized estimates and to avoid inconsistencies in data collection, metrics used, and usefulness of the monitoring efforts. We compared seed yield estimates derived from a suite of commonly used seed production assessment methods with those from soil core samples across six National Wildlife Refuges in the southeastern U.S. The most parsimonious model included only common plant species and a single visual assessment of overall coverage (1-5) and seed quality (1-4) for each moist-soil unit ($r^2_{adj} = 0.71$). Generally, models that included only common plant species and a visual estimate of seed yield for moist-soil wetlands overall had greater support than models that included all plant species and those that included data from subplots ($n = 10$) nested within moist-soil wetlands. Experience level of observer had a moderate effect on accuracy ($r^{2mar} = 0.20$) and geographic range increased variation in overall seed yield estimates within moist-soil wetlands. Notably, we found that similar indices developed in different geographic regions performed well across the Southeast, but a widely used index based on estimates of seed yield for individual plant species performed poorly in this study. Standardizing the use of a single, efficient, and reliable method to estimate seed abundance in moist-soil wetlands will provide wetland managers the ability to consistently estimate performance relative to objectives, evaluate management actions, and track trends on National Wildlife Refuges in the southeastern U.S.
Large-scale assessment of rapid monitoring methods for estimating moist-soil seed production

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Abstract

Federal, state, and private entities manage seasonal flooded, shallow wetlands to provide food and other habitat resources for wetland-dependent migratory birds, including migrating and wintering waterfowl. Individual National Wildlife Refuges managed by the U.S. Fish and Wildlife Service annually monitor seed production in moist-soil wetlands to track performance relative to regional foraging habitat objectives and to evaluate local habitat management activities. The National Wildlife Refuge System does not currently have a standard sampling protocol, and thus seeks a reliable rapid assessment method for estimating seed production to achieve standardized estimates and to avoid inconsistencies in data collection, metrics used, and usefulness of the monitoring efforts. We compared seed yield estimates derived from a suite of commonly used seed production assessment methods with those from soil core samples across six National Wildlife Refuges in the southeastern U.S. The most parsimonious model included only common plant species and a single visual assessment of overall coverage (1-5) and seed quality (1-4) for each moist-soil unit ($r^2_{adj} = 0.71$). Generally, models that included only common plant species and a visual estimate of seed yield for moist-soil wetlands overall had greater support than models that included all plant species and those that included data from subplots ($n = 10$) nested within moist-soil wetlands. Experience level of observer had a moderate effect on accuracy ($r^2_{mar} = 0.20$) and geographic range increased variation in overall seed yield estimates within moist-soil wetlands. Notably, we found that similar indices developed in different geographic regions performed well across the Southeast, but a widely used index based on estimates of seed yield for individual plant species performed poorly in this study. Standardizing the use of a single, efficient, and reliable method to estimate seed abundance in moist-soil wetlands will provide wetland managers the ability to consistently estimate performance relative to objectives, evaluate management actions, and track trends on National Wildlife Refuges in the southeastern U.S.

Keywords: duck-energy-days, moist-soil wetlands, National Wildlife Refuge, rapid assessment, seed yield, Southeast, waterfowl

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Conservation planning efforts for migrating and wintering waterfowl areas assume that food availability is a reasonable metric for evaluating wetland quality and other habitat resource needs (Wilson and Esslinger 2002; Lower Mississippi Valley Joint Venture 2015). Bioenergetic models based on food availability have become the standard approach used by most conservation partners with substantial waterfowl foci during the non-breeding period in North America (Petrie et al. 2011). Due to extensive loss and degradation of natural wetlands and changing agricultural practices that limit abundance of waste grain on the landscape, federal- and state-managed lands in the Southeast US are integral in providing food for waterfowl in support of conservation objectives of North American Waterfowl Management Plan (Lower Mississippi Valley Joint Venture 2015). To meet the energy demand of waterfowl populations and achieve local habitat objectives, many federal and state wildlife management agencies manage natural wetlands to promote desirable moist-soil plants in combination with planting cereal grains to provide a diversity of high-energy food resources in wetland areas.

Methods for quantifying annual moist-soil seed yield have been widely used to evaluate local and regional management objectives, largely because moist-soil seed provides important energetic resources for migrating and wintering waterfowl (Low and Bellrose 1944, Fredrickson and Taylor 1982). In addition to energy from carbohydrates, moist-soil seeds provide essential amino acids and minerals that are critical to the maintenance of annual cycle events such as migration, winter survival, molt, and reproduction. State and federal waterfowl area managers
aim to produce high yielding moist-soil wetlands to provide abundant foraging habitat to meet
the energetic demands of waterfowl (Heitmeyer and Fredrickson 1981; Kaminski and Gluesing
1987; Raveling and Heitmeyer 1989). Monitoring of annual moist-soil plant productivity is
essential to track performance relative to habitat objectives and quantify contributions to
ergetic goals set by Migratory Bird Joint Ventures, a collaborative partnership established
under the North American Waterfowl Management Plan to help conserve the continent’s
waterfowl populations and habitats (Williams et al. 1999; Humburg et al. 2018). Thus, local
managers need to produce time-efficient and reliable seed yield estimates to generate consistency
in sampling efforts to ensure an adequate amount of food energy is available to support wintering
waterfowl populations.

Rapid assessment methods for estimating seed yield include visual indices that are
quicker to implement and more cost-effective than direct methods which require processing soil
or plant samples in the laboratory (Kross et al. 2008; Hagy et al. 2011; Osborn et al. 2017).
Rapid assessment indices were created as a tool for area managers and field biologists to track
trends in seed production in a time efficient manner. Without a method to quickly estimate seed
production of a wetland, managers must process soil cores or use other resource-intensive
methods to quantitatively assess moist-soil seed productivity (Penny et al. 2006). These methods
are impractical for routine monitoring.

Numerous methods to estimate seed yield in moist-soil wetlands have been developed,
including models relying on plant morphometrics (Gray et al. 1999a; Gray et al. 2009), visual
indices (Naylor et al. 2005), soil-sampling (Kross et al. 2008), and others (e.g., Penny et al.
2006). Initial studies used linear regression to developed species-specific models to predict seed
yield from morphological measurements (e.g., plant height and inflorescence diameter; Laubhan
and Fredrickson 1992; Gray et al. 1999b; Sherfy and Kirkpatrick 1999), but plant measurements
were tedious and time-consuming to obtain and model predictions were biased when used
outside the region where they were developed (Gray et al. 1999a; b). Gray et al. (2009) improved
the model performance with a more time-efficient process using desktop or portable area
scanners. While improved, the plant morphometric-based method was limited because the linear
models were created from a small number of plant species (n = 9; Gray et al. 2009) and the
method requires the collection and processing of plant specimens requiring additional time and
cost.
Naylor et al. (2005) developed a simplified visual foraging habitat quality index for moist-soil wetlands in California, USA. This visual index was simple to use and somewhat robust to observer bias which made it optimal for use across large geographic areas a part of a coordinated monitoring plan. Unfortunately, that index was developed partially from species that do not occur in the central and eastern United States. An attempt to validate the methods in Illinois indicated potential usefulness of the index outside of the region for which it was developed (Stafford et al. 2011), but subsequent research indicated that the index needed to be adjusted using constants to more accurately estimate seed yield in the Midwest (McClain et al. 2019). However, validation of these rapid assessment indices across a large geographic area in the central and eastern U.S. was needed before wetland managers could apply these efficient techniques broadly to assess seed production in moist-soil wetlands.

We estimated seed density using standard core sampling procedures for comparison with seed production estimates from previously published rapid assessment methods (Laubhan and Fredrickson 1992; Naylor et al. 2005; McClain et al. 2019) and variations of these methods in moist-soil wetlands across the Southeast. Our objectives were to assess accuracy of the visual assessment methods by comparing seed yield estimates to core-sample estimates and to test effects of observer identity, observer experience, and geographic variation on seed production estimates. We anticipate that this research will support federal, state, and private entities in generating wetland monitoring protocols to evaluate local management objectives and for assessing the regional contributions to continental objectives of the NAWMP.

**Study Area**

We sampled actively managed moist-soil wetlands across six National Wildlife Refuges (NWRs, Refuges), contained within three U.S. Fish and Wildlife Service (USFWS) Interior Regions and four states along a relatively similar latitudinal range, including Arkansas, Illinois, Mississippi, and North Carolina. Included in this research were Alligator River (NC, \(n = 2\)), Coldwater River (MS, \(n = 2\)), Mattamuskeet (NC, \(n = 2\)), Overflow (AR, \(n = 4\)), Two Rivers (IL, \(n = 5\)), and Dale Bumpers White River (AR, \(n = 3\)) NWRs (Figure 1). Common plant species occurring in moist-soil wetlands across this region included barnyard grass *Echinochloa crus-gali*, coast cockspur grass *Echinchloa walteri*, fall panicum *Panicum dichotomiflorum*, nodding smartweed *Polygonum lapathifolium*, Pennsylvania smartweed *Polygonum pensylvanicum*,...
swamp smartweed *Polygonum hydropiperoides*, reedroot flatsedge *Cyperus esculentus*, and Amazon sprangletop *Leptochloa panicoides*. The timing of dewatering of moist-soil wetlands during the growing season generally occurred during April–June.

Alligator River (153,000 acres) and Mattamuskeet (50,180 acres) NWRs are located in the Atlantic Flyway and the USFWS South Atlantic-Gulf Region (Interior Region 2). Alligator River NWR contains 1,900 acres of actively managed moist-soil wetlands, along with upland and lowland forest, open water, fresh and brackish marshes, and shrub wetlands (USFWS 2008a). Mattamuskeet NWR contains diverse land cover types such as open water, cropland, freshwater marshes, and approximately 2,000 acres of actively managed moist-soil wetlands (USFWS 2008b).

Within the Mississippi Flyway, we surveyed wetlands at Two Rivers, Dale Bumpers White River, Coldwater River, and Overflow NWRs. Two Rivers NWR is in the USFWS Great Lakes Region (Interior Region 3) and lies at the confluence of the Mississippi and Illinois rivers near Brussels, Illinois. There are eight moist-soil wetlands encompassing nearly 300 acres, some of which are managed by low water dikes rather than water control structures (USFWS 2004). Dale Bumpers White River, Coldwater, and Overflow NWRs are located in the USFWS Mississippi Basin Region (Interior Region 4). Dale Bumpers White River NWR contains nearly 160,000 of contiguous bottomland hardwood forest, half of which is controlled by water control infrastructure and the remainder influenced by flood-pulse inundation of the White and Arkansas rivers. The remainder of Dale Bumpers Whiter River NWR contains permanent or semi-permanent lakes, swamps, agricultural areas, and 320 acres of moist-soil wetlands. Coldwater NWR is a small wetland complex (2,374 acres) located in the Mississippi Alluvial Valley near Crowder, Mississippi. Coldwater River NWR contains 25 former aquaculture ponds that were converted to moist-soil wetlands (275 acres) for waterbird and waterfowl habitat. Overflow NWR (13,973 acres) contains 1,600 acres of reclaimed agricultural ground converted to moist-soil wetlands (USFWS 2005), emergent marsh, and forested wetlands.

**Methods**

**Field Estimates and Sampling**

We estimated seed density (kg/ha) in 18 moist-soil wetlands during early autumn (September 26 – October 31, 2018) after seed maturation and before flooding (Data S1). Within
each wetland, we selected 10 plots (5 m radius) along transects that spanned the entire wetland using a systematic random design (Hagy and Kaminski 2012a). The first plot along each transect was selected by choosing a random distance 20–100 m from the transect starting point and each subsequent plot was located at approximately equal distance apart to increase efficiency and ensure spatial representation (Hagy and Kaminski 2012a; Figure 2). We collected five soil cores (5 cm deep, 9 cm wide) in each plot using a custom soil corer with a plunger (Osborn and Hagy 2014). One soil core was collected in the plot center and the other four were collected approximately 4.5 m from the center at each cardinal direction. Seeds were threshed from plants by hand within 1-m of sample location before soil core samples were taken. The five soil core samples within each plot were homogenized in a bucket and frozen within 48 hr for subsequent processing. We collected a total of 50 soil core samples from each moist-soil wetland sampled ($n = 18$).

We then collected species composition and structural data using metrics derived from three different commonly used rapid assessment methods (i.e., Laubhan and Fredrickson 1992; Naylor et al. 2005; McClain et al. 2019). We recorded proportional cover (%) of all plant species that accounted for ≥1% of the total area of the plot. We visually estimated overall quality (i.e., unified estimate of seed head size and density; 1 [low] – 4 [high]), seed head size (small, moderate, large), and seed head density (low, moderate, high) for each species in each plot (Naylor et al 2005). Because there is often vertical stratification of plants in moist-soil wetlands, we allowed the total of coverage estimates to exceed 100%. We also measured plant height (cm), seed head height (cm), seed head diameter (cm), and number of seed heads per species within a 25 x 25 x 100 cm sampling frame (Laubhan and Fredrickson 1992).

**Laboratory Processing**

In the laboratory, we thawed for ~24 hr and then soaked soil core samples in a diluted hydrogen peroxide solution to disassociate clay particles (Hagy and Kaminski 2012a, Hagy and McNight 2016). After ~20 min of soaking, we washed soil cores through a #10 (2 µm) and a #60 (0.25 µm) stainless steel sieve (Science First, Yulee, FL, USA) to separate large and small seeds from soil and other material. We placed large (#10 sieve) and small (#60 sieve) samples on separate paper plates, labelled them accordingly, and allowed them to air dry ≥24 hr. Small samples were subsampled to 25% by dry weight and all seeds and tubers were removed by hand and identified to the lowest possible taxonomic classification (Hagy et al. 2011). After sorting
and identification, seeds were oven dried at 65°C for 24 hr, and weighed to the nearest 0.1 mg.

We applied correction factors to seed weights according to seed size category (1.07 for large ≥8.0 mm³; 1.10 for medium 1.8–4.0 mm³; 1.35 for small ≤0.4 mm³) to account for seed loss in the washing, sieving, and sorting processes (Hagy et al. 2011).

**Statistical Analysis**

We estimated total seed and tuber density (kg[dry]/ha) for each plot, wetland, and NWR. We excluded species not known to be consumed by ducks from analysis for both soil cores and rapid assessment data (Hagy and Kaminski 2012a; Osborn et al. 2017). We used an analysis of variance to test for differences in seed yield by NWR using package stats in Program R (version 2.15.0; R Core Team 2020). We used a Tukey’s Honest Difference pairwise comparison to test for differences when the main effect was significant (α = 0.05). We examined histograms, variances, and residual plots to ensure data met assumptions of analyses (Littell et al. 2006).

We built 21 seed production indices using previously published indices (Laubhan and Fredrickson 1992; Naylor et al. 2005; McClain et al. 2019) and modifications thereof. We tried several modifications of the index evaluated by Naylor et al. (2005) by extending their methods to our data, modifying the quality score range by dividing or consolidating the seed head size and seed head quality scores, increasing coverage score range, and modifying the number of species included depending on their proportional coverage. We also evaluated plot-based (i.e., subsampling, 10 plots / wetland) metrics (i.e., Laubhan and Fredrickson [1992]; Naylor et al. [2005]; and odd-numbered indices) and whole-wetland scale indices (i.e., no subsampling; even-numbered indices). Rapid assessment methods (Table 1) identified as Index 1a-8a used all species of dietary value to waterfowl, whereas Index 1b-8b used only the dominant species found in soil core samples (top six species, in terms of occurrence).

We used model selection to evaluate three independent model sets to examine the effects of observer, observer experience level, geographic area, and rapid assessment method on seed densities relative to core samples. We performed all statistical analyses in Program R. Adjusted r² values were computed for all models using the package MumIn (Gray et al. 1999b; Naylor et al. 2005). Model selection was based on Akaike’s Information Criterion corrected for small sample size (AICc), difference between current and top model (ΔAICc), and Akaike weights (ω; Akaike 1973; Burnham and Anderson 2002). We considered all models within 2.0 ΔAICc from the top ranked model competitive.
To test the effects of geographic variation on rapid assessment methods, we isolated survey data from a single experienced observer that sampled all moist-soil wetlands across all NWRs. Most observers differed among NWRs as local staff served as observers on their own properties, but a few observers collected data on multiple NWRs and one observer with extensive experience collected data on all NWRs. Using this single-observer sample controlled for potential effects of observer identity and observer experience in the first model set, which was mainly comparing different indices. The first model set included 21 models, each with a different index as the dependent variable and seed density estimates from core samples as the independent variable (Model set 1). We used linear models with the package stats to determine the best indices independent of observer experience and observer identity. Additionally, we reran the top-ranked models from Model set 1 after censoring data from NWRs outside of Arkansas (Model set 1b) in order to compare the effects of large-scale geographic variation on index performance.

In the second model set, we controlled for geographic variation by limiting the analysis to only data from four wetlands in Dale Bumpers White River and Overflow NWRs where the same five observers conducted all observations. We used general linear mixed effects models in package lme4 with observer as a fixed effect and NWR as a random effect to test the fit of top models from model set 1 (Bates et al. 2014). The marginal and conditional $r^2$ values were computed using the package performance (Nakagawa and Schielzeth 2013).

In the third model set, we examined the effects of observer experience on seed production index. We used data from all wetlands ($n = 18$) and observers ($n = 17$) by assigning each observer a score (i.e., low and high) based on their experience level in managing and monitoring moist-soil vegetation. We used general linear mixed models with observer experience level as a fixed effect and included NWR as the random effect to test top model performance from model set 1 (Bates et al. 2014). We calculated marginal and conditional $r^2$ values using the Nakagawa method in the package performance (Nakagawa and Schielzeth 2013).

**Results**

Seeds of species not consumed by waterfowl accounted for 12% of all seed mass from soil cores while important waterfowl forage species accounted for 88%. The most prevalent desirable seed species were barnyard grass (78% occurrence), Pennsylvania smartweed (75%...
occurrence), common spikerush *Eleocharis palustris* (44% occurrence), sprangletop *Leptochloa fascicularis* (44% occurrence), fall panicum (42% occurrence), and browntop signal grass *Urochloa fusca* (22% occurrence), which were used in reduced species indices (i.e., set “b”). In model set 1a where we excluded effects of observer and observer experience, Index 2b ($\beta = 1.00$; CI = 0.67 – 1.33; $r^2_{\text{adj}} = 0.71$), Index 8b ($\beta = 1.00$; CI = 0.67 – 1.33; $r^2_{\text{adj}} = 0.71$), and Index 4b ($\beta = 1.00$; CI = 0.64 – 1.36; P < 0.001; $r^2_{\text{adj}} = 0.69$) were the highest-ranking rapid assessment methods and collectively accounted for 86% of the model weight (Table 1). Indices that included all moist-soil plant species were generally less competitive than indices with reduced species. In model set 1b when controlled for geographic variation, observer effects, and observer identity (i.e., censoring all data but Arkansas NWRs and one experienced observer), predictive power of these top models increased (Index 2b [$r^2_{\text{adj}} = 0.92$], Index 8b [$r^2_{\text{adj}} = 0.92$], and Index 4b [$r^2_{\text{adj}} = 0.90$]).

In the second model set, the null model was competitive ($\Delta$AICc = 0.09) and fixed effects accounted for little of the variation ($r^2_{\text{mar}} = 0.01$). Thus, incorporating the effect of observer did not meaningfully improve index capacity to predict seed yield. The random effect of wetland accounted for a substantial amount of variation in all models ($r^2_{\text{con}} \geq 0.95$), indicating much larger variation associated with location difference than observer identity (Table 2).

The third model set that explored effects of observer experience on top performing indices had three competitive models (Table 3). Index 2b ($\beta = 0.68$; CI = 0.50 – 0.85), Index 4b ($\beta = 0.53$; CI = 0.39 – 0.66), and Index 8b ($\beta = 0.31$; CI = 0.23 – 0.39) with “observer experience” as a fixed effect accounted for 97% of the model output weight. Although models with observer experience ranked higher than models without, the difference in marginal variance explained was very small, whereas the random effect of NWR explained substantially more of the variation ($r^2_{\text{con}} = 0.87$).

**Discussion**

Rapid seed production indices were reasonably robust to geographic variation, observer experience, and observer bias across moist-soil wetlands in the Southeast US. Although several indices performed reasonably well, index 2b was the most parsimonious and we recommend it for use across the Southeast. Although indices 4b and 8b were competitive, they require collection of species composition data <5% coverage and use of an additional constant in the
regression equation. Index 2b is simple and straightforward – it requires visual estimates of coverage (1-5) and quality (1-4) ranking scores (i.e., based on general seed head density and size) for six moist-soil plant species (i.e., barnyard grass, Pennsylvania smartweed, spikerush, sprangletop, fall panicum, and signal grass) that are commonly consumed by waterfowl and frequently occur in managed moist-soil wetlands. This index includes slight modifications to the previously published index by Naylor et al. (2005) that has been used in Illinois (Stafford et al. 2011; McClain et al. 2019) and other locations (Loges et al. 2021). Index 2b is simple, efficient to implement in the field, robust to variation in observer experience levels as it requires observers to learn only common plant species and provides relatively high explanatory power considering its simplicity. The index can be completed in as little as three minutes, excluding time spent by observers traversing the moist-soil wetland to assess vegetation communities.

Soil cores are typically considered the standard technique in estimating seed production, but processing samples is extremely time and labor intensive making them impractical for use at a large scale or on a recurring basis. Our soil-core estimates suggest that 88% of the seed produced across our study areas were species known to be consumed by ducks and are beneficial to foraging waterfowl. Some wetland managers use constant values (e.g., 600 kg/ha) for seed yield in moist-soil wetlands that have been adopted for some conservation planning efforts (Kross et al. 2008). Constant estimates of seed yield require the assumption that the field produced an average amount of seed. However, this approach doesn’t allow evaluation of annual variation or management actions and is inherently inaccurate because moist-soil seed production is known to vary across moist-soil wetlands and within wetlands between years (Bowyer et al. 2005; Kross et al. 2008; Stafford et al. 2011; Hagy and Kaminski 2012b). Soil core estimates in this study found seed production to be extremely variable across NWRs and moist-soil wetlands; thus, rapid assessment methods that are simple and time-efficient enough to use annually over a range of geographic areas are critical to helping wetland managers conduct monitoring to support adaptive resource management.

Index 2b was relatively accurate, with only a small portion of the variation unaccounted for in the model. There were numerous observers (n = 17) involved in this study with varying levels of experience in moist-soil management and estimating seed yield. When incorporating all observers, we found that the experience level of an individual had a positive effect on seed yield estimates, accounting for 20 – 22% of the variation in model. In contrast, Naylor (2002)
determined that observer experience had no effect on seed yield estimates, but he did caution that estimates can differ between observers occasionally. In additional to observer experience, geographic variation had an effect on observer estimates. When using estimates from one experienced observer and comparing the predictive power of Index 2b across all Refuges sampled to only Refuges in Arkansas, the predictive power increased from $r^2_{adj} = 0.71$ to $r^2_{adj} = 0.92$. A brief annual training led by personnel familiar with regional moist-soil plant species and estimating seed production using rapid assessment indices could potentially decrease observer error introduced by varying levels of experience and make estimates more accurate. Likewise, opportunities exist to train wetland managers of state agencies or private land managers to identify common species, estimate seed yield, and interpret the index. Collective and coordinated monitoring of seed yield on federal, state, and private land could prove more effective for assessing regional trends and contributions to conservation planning efforts. When possible, it is likely prudent for a small number of observers to monitor and record seed yield estimates on as many moist-soil wetlands as possible to reduce observer bias. For example, a single biologist could survey all the moist-soil wetlands within their administrative complex or region instead of individual site managers surveying their own moist-soil wetlands independently.

Index 2b had slightly lower predictive power than several previously published assessment methods that were more resource-intensive (Gray et al. 1999a; Gray et al. 2009), but the resource intensity required to collect, dry, press, and scan or measure plant inflorescences make the tradeoff in accuracy more than reasonable for most wetland managers. As current resource management agencies experience restricted budgets and reduced staffing, the efficiency of Index 2b makes it more practical to use than more intensive indices with slightly higher predictive power. Conversely, the Laubhan and Fredrickson (1992) method, which uses 11 common species, performed poorly in our study. In fact, and despite being semi-quantitative, the Laubhan and Fredrickson (1992) method was the poorest method we tested and would be unsuitable for use on NWRs based on this dataset. Although it is unclear why the method performed so poorly in our study areas, we noted that predicted yields of some species, particularly redroot flatsedge, were unreasonably high relative to soil core estimates (i.e., >3,000 kg/ha).

Indices that used the most common plant species (i.e., indices ending in “b”) performed better than indices that used all species that are beneficial to waterfowl (i.e., indices ending in
“a”). We suspect that indices using all plant species <1% coverage are artificially inflated due to plant diversity, because seed production is estimated equivalently for each species in the wetland. Many of the included species in the indices ending in “a” may not produce substantial amounts of seed yet were treated equal to species that were prolific seed producers. We suspect that incorporating those plant species may have inflated the estimated seed yield, thus resulting in poor performing models. Another issue that we noticed in our data was that moist-soil wetlands composed of prolific seed-producing species (e.g., barnyardgrass, sprangletop) tended to be underestimated by the index while moist-soil wetlands that were dominated by light-seeded species (e.g., fall panicum) tended to be overestimated by indices. Our indices didn’t incorporate yield potential by species, which can be highly variable. Thus, wetland managers needing more accurate estimates, especially with wetland dominated by heavy-seeded species, may consider other morphometric indices that are more resource intensive (Gray et al. 1999a; Gray et al. 2009).

Supplemental Material

Data S1. Copy of raw data including National Wildlife Refuge (NWR), name of field within moist-soil wetlands (FieldName), date, observer, plot, % of plot that was vegetated (%VegCover), % of entire field visible (%Visibility), kg/ha of moist soil seeds based on visual assessment (Vis kg/ha), plant species (PlantSp), % coverage of plot by plant species (%Cover), overall quality estimate by species (OverallQuality), mean height by species in cm (PlantHeightCM), rank of seed head size by species (HeadSize), rank of density of seed heads by species in plot (HeadDensity), length of seed head (HeadLength), diameter of seed head (HeadDiameter), and number of seed heads per plant (Head#). Data was collected by University of Arkansas – Monticello and US Fish and Wildlife Service personnel in moist soil wetlands on National Wildlife Refuges in Arkansas, Mississippi, Missouri, and North Carolina during September 26 – October 31, 2018.

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**Figures Captions and Tables**

**Figure 1.** Study area for estimating seed yield and collecting soil core samples in moist-soil wetlands on National Wildlife Refuges during September 26 – October 31, 2018.
Figure 2. Hypothetical moist soil wetland and sampling plot layout for estimating seed yield and collecting soil core samples on National Wildlife Refuges during September 26 – October 31, 2018.
Table 1. Rapid assessment methods and associated description, regression equation, and citations for various seed production indices used in estimating seed yield in moist soil wetlands on National Wildlife Refuges in Arkansas, Mississippi, Missouri, and North Carolina during September 26 – October 31, 2018

| Rapid Assessment Method | Description of predictor variables and methods | Regression Equation |
|-------------------------|-----------------------------------------------|---------------------|
| Laubhan                 | Uses plant height (cm), seed head height (cm), seed head diameter (cm), and number of seed heads in plots (625 cm² x 100 cm tall) as variables in species specific regression equations for 11 common moist-soil plant species to predicted seed yield. | Species specific equations see Laubhan and Fredrickson (1992) |
| Visual                  | Simple visual estimates of total seed yield (kg/ha) of entire wetland unit by an experienced observer. Visual estimates in this study provided by Heath Hagy, U.S. Fish and Wildlife Service. | N/A |
| Naylor a-b              | Estimates quality (rank 1-4) and stem density (rank 1-5) in 10-m diameter plots (10 plots/unit) to get a Seed Production Index (SPI). Quality is based on a combination of seed head size (large, small) and seed head density (high, moderate, low). The SPI* is input into a published regression equation to predict seed yield. | 19.01 * SPI – 195.12 |
| Index 1a                | Estimates quality (rank 1-4) and stem density (rank 1-5) in 10-m diameter plots (10 plots/unit) to get a SPI. Quality is based on a combination of seed head size (large, small) and seed head density (high, moderate, low). | 42.43 * SPI – 616.47 |
| Index 2a                | Estimates quality (rank 1-4) and stem density (rank 1-5) once per wetland (one estimate/unit) to get a SPI. Quality is based on a combination of seed head size (large, small) and seed head density (high, moderate, low). | 22.546 * SPI – 174.425 |
| Index | Description | Equation |
|-------|-------------|----------|
| 3a    | Estimates quality (rank 1-6) and stem density (rank 1-5) in 10-m diameter plots (10 plots/unit) to get a SPI. Quality is based on a combination of seed head size (large, medium, small) and seed head density (high, moderate, low). | 32.310 * SPI – 647.016 |
| 4a    | Estimates quality (rank 1-6) and stem density (rank 1-5) once per wetland (1 estimate/unit) to get a SPI. Quality is based on a combination of seed head size (large, medium, small) and seed head density (high, moderate, low). | 16.049 * SPI – 133.357 |
| 5a    | Estimates quality (rank 1-6) and stem density (rank 1-10) in 10-m diameter plots (10 plots/unit) to get a SPI. Quality is based on a combination of seed head size (large, medium, small) and seed head density (high, moderate, low). | 18.688 * SPI – 376.602 |
| 6a    | Estimates quality (rank 1-6) and stem density (rank 1-10) once per wetland (1 estimate/unit) to get a SPI. Quality is based on a combination of seed head size (large, medium, small) and seed head density (high, moderate, low). | 12.795 * SPI – 160.103 |
| 7a    | Estimates quality (rank 1-4) and stem density (rank 1-5) in 10-m diameter plots (10 plots/unit) to get a SPI. Quality is based on a combination of seed head size (large, small) and seed head density (high, moderate, low). The SPI multiplied by a correction factor (1.72) and input into a published regression equation (Naylor et al. 2005) to predict seed yield. | 24.669 * (SPI*1.72) – 616.474 |
| 8a    | Estimates quality (rank 1-4) and stem density (rank 1-5) once per wetland (1 estimate/unit) to get a SPI. Quality is based on a combination of seed head size (large, small) and seed head density (high, moderate, low). The SPI multiplied by a correction factor (1.72) and input into a published regression equation (Naylor et al. 2005) to predict seed yield. | 13.108 * (SPI*1.72) – 174.425 |
| 1b    | Same as Naylor a, but only uses the six dominant species. | 19.01 * SPI – 195.12 |
| 1b    | Same as Index 1a, but only uses the six dominant species. | 34.4786 * SPI – 0.1686 |
| Index   | Description                                                                 | Equation                                      |
|---------|------------------------------------------------------------------------------|-----------------------------------------------|
| 2b      | Same as Index 2a, but only uses the six dominant species.                     | 29.698 * SPI – 50.201                         |
| 3b      | Same as Index 3a, but only uses the six dominant species.                     | 25.594 * SPI + 3.573                          |
| 4b      | Same as Index 4a, but only uses the six dominant species.                     | 22.078 * SPI – 42.725                         |
| 5b      | Same as Index 5a, but only uses the six dominant species.                     | 14.912 * SPI + 104.876                        |
| 6b      | Same as Index 6a, but only uses the six dominant species.                     | 13.683 * SPI + 49.895                         |
| 7b      | Same as Index 7a, but only uses the six dominant species.                     | 20.0456 * (SPI * 1.72) – 0.1686                |
| 8b      | Same as Index 8a, but only uses the six dominant species.                     | 17.266 * (SPI * 1.72) – 50.201                |

Index 2b, 3b, 4b, 5b, 6b, 7b, and 8b are models that use the six dominant species from the data.

Indices ending in “a” denote models that use all species of value to waterfowl.

Indices ending in “b” denote models that use the six dominant species from the data.

Laubhan and Fredrickson 1992
Naylor et al. 2005
McClain et al. 2019
Table 2. Model output of rapid assessment models ability to predict seed yield while isolating the effect of observer used in evaluating common moist-soil seed yield indices across four National Wildlife Refuges in the Southeastern United States during autumn 2018.

| Model a | K | ΔAICc | $W_i$ | Cum. $W_i$ | $R^2_{adj}$ |
|---------|---|-------|------|-----------|-----------|
| Index 8b | 3 | 0.00  | 0.36 | 0.36      | 0.71      |
| Index 2b | 3 | 0.00  | 0.36 | 0.72      | 0.71      |
| Index 4b | 3 | 1.70  | 0.15 | 0.87      | 0.69      |
| Visual | 3 | 3.16  | 0.07 | 0.95      | 0.66      |
| Index 6b | 3 | 6.26  | 0.02 | 0.96      | 0.60      |
| Naylor b | 3 | 7.02  | 0.01 | 0.97      | 0.58      |
| Index 7b | 3 | 7.02  | 0.01 | 0.98      | 0.58      |
| Index 1b | 3 | 7.02  | 0.01 | 0.98      | 0.58      |
| Index 3b | 3 | 8.09  | 0.01 | 0.99      | 0.55      |
| Index 5b | 3 | 10.77 | 0.00 | 0.99      | 0.48      |
| Naylor a | 3 | 10.87 | 0.00 | 0.99      | 0.48      |
| Index 7a | 3 | 10.87 | 0.00 | 0.99      | 0.48      |
| Index 1a | 3 | 10.87 | 0.00 | 0.99      | 0.48      |
| Index 3a | 3 | 10.90 | 0.00 | 1.00      | 0.48      |
| Index 6a | 3 | 11.04 | 0.00 | 1.00      | 0.47      |
| Index 8a | 3 | 11.62 | 0.00 | 1.00      | 0.46      |
| Index 2a | 3 | 11.62 | 0.00 | 1.00      | 0.46      |
| Index 4a | 3 | 12.16 | 0.00 | 1.00      | 0.44      |
| Index 5a | 3 | 14.00 | 0.00 | 1.00      | 0.38      |
| Laubhan | 3 | 16.09 | 0.00 | 1.00      | 0.30      |
| NULL | 2 | 19.68 | 0.00 | 1.00      | 0.00      |

Indices 1a-8a denote models that used all species of dietary value and indices 1b-8b denote models that used reduced species.
Table 3. Model output of rapid assessment models ability to predict seed yield with the effect of observer and limited geographic variation used in evaluating common moist-soil seed yield indices across four National Wildlife Refuges in the Southeastern United States during autumn 2018.

| Model          | K | ΔAICc | AICcWt | Cum.Wt | Mar.R² | Con.R² |
|----------------|---|-------|--------|--------|--------|--------|
| Index 2b + OBS | 5 | 0.00  | 0.29   | 0.29   | 0.01   | 0.96   |
| NULL           | 3 | 0.09  | 0.28   | 0.57   | 0.00   | 0.95   |
| Index 4b + OBS | 5 | 0.88  | 0.19   | 0.75   | 0.01   | 0.96   |
| Index 8b + OBS | 5 | 1.97  | 0.11   | 0.86   | 0.01   | 0.96   |
| Index 2b       | 4 | 2.88  | 0.07   | 0.93   | 0.01   | 0.96   |
| Index 4b       | 4 | 3.83  | 0.04   | 0.98   | 0.01   | 0.96   |
| Index 8b       | 4 | 4.91  | 0.02   | 1.00   | 0.01   | 0.96   |

Table 4. Model output of rapid assessment models ability to predict seed yield using all observers, observer experience, and incorporating geographic variation into the models used in evaluating common moist-soil seed yield indices across four National Wildlife Refuges in the Southeastern United States during autumn 2018.

| Model          | K | ΔAICc | AICcWt | Cum.Wt | Mar.R² | Con.R² |
|----------------|---|-------|--------|--------|--------|--------|
| Index 2b + OBS_EX | 5 | 0.00  | 0.45   | 0.45   | 0.20   | 0.87   |
| Index 4b + OBS_EX | 5 | 0.66  | 0.33   | 0.78   | 0.22   | 0.87   |
| Index 8b + OBS_EX | 5 | 1.74  | 0.19   | 0.97   | 0.22   | 0.87   |
| Index 2b        | 4 | 6.59  | 0.02   | 0.99   | 0.20   | 0.87   |
| Index 4b        | 4 | 7.87  | 0.01   | 0.99   | 0.20   | 0.87   |
| Index 8b        | 4 | 8.95  | 0.01   | 1.00   | 0.20   | 0.87   |
| NULL           | 3 | 43.79 | 0.00   | 1.00   | 0.00   | 0.83   |
Randomly selected

Established transects

Moist-soil unit

Plot (10-m diameter)

Soil core (10-cm diameter, 5-cm depth)

1-meter threshed
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**Supplemental Material**

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