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Research Article-Editor's Choice

Assessment of Range Planting as a Conservation Practice[☆]

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ABSTRACT

Natural Resource Conservation Service Range Planting – Conservation Practice Standards provide guidelines for making decisions about seedbed preparation, planting methods, plant materials selection, seeding rate, seeding depth, timing of seeding, postplanting management, and weed control. Adoption of these standards is expected to contribute to successful improvement of vegetation composition and productivity of grazed plant communities. Also expected are some specific conservation effects, such as improved forage for livestock; improved forage, browse, or cover for wildlife; improved water quality and quantity; reduced wind or water erosion; and increased carbon sequestration. The success of specific conservation practices and the magnitude of conservation effects are highly dependent on ecological-site characteristics, the initial degree of deviation from desired site characteristics, and weather, all of which are highly variable in both time and space. Previous research has produced few studies directly linking range planting conservation practices to conservation effects. Assessment of conservation effects attributed to rangeland planting practices must, therefore, be separated into two components: 1) evidence of the degree to which specific management practices have been shown to result in desirable vegetation change and 2) evidence supporting positive conservation effects of alternative vegetation states. The aggregate literature generally supports both 1) the existing conservation practice recommendations for rangeland seeding and 2) the inherent assumption that if these practices are successful, they will result in beneficial conservation effects. High spatial and temporal variability in these systems, however, may limit the success of generic or prescriptive management practices. Current conservation practice recommendations could be improved by incorporating more direct linkages to the ecologically based technical literature, more up-to-date information on adaptive management strategies in highly variable rangeland systems, and integration of monitoring strategies designed to directly test the efficacy of specific conservation practices.

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Introduction

The Natural Resources Conservation Service (NRCS) Range Planting Conservation Practice Standard (CPS 550) is used to develop NRCS management recommendations for improving vegetation composition and productivity of grazed plant communities when the existing ecological state is insufficient to meet management goals and natural recovery toward a more desirable state is not expected. Successful implementation

of range planting treatments is assumed to confer some or all of the following conservation effects: improved forage availability for grazing animals; improved wildlife habitat; reduced erosion by wind and/or water; improved water quality and quantity; and increased carbon sequestration.

The relevant spatial domain for CPS 550 includes rangelands in 17 western states that exhibit diverse vegetation types, management priorities, and climatic syndromes and that also vary internally along latitudinal and elevational gradients (Barbour and Billings 2000; Natural Resources Conservation Service 2006). Resource management issues common to all areas, however, are a generally arid or semiarid climatology, high annual and seasonal variability in weather, and intense competition from introduced annual weeds or expanding populations of native woody plants (Hardegree et al. 2012a, 2012b).

The success of specific conservation practice recommendations and the potential ecological outcomes realized are highly dependent on ecological site characteristics, the initial degree of deviation from desired site characteristics, and weather, all of which are highly variable in

[☆] Superscript numbering throughout the text indicates that an expanded list of reference citations may be found.

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both time and space. This variability has perhaps contributed to the relatively short-term and site-specific nature of most rangeland seeding studies, as well as the general lack of longer-term studies directly linking range planting conservation practices and conservation effects *per se*. This linkage is primarily derived indirectly through 1) evidence of the degree to which specific planting techniques have been shown to produce successful plant establishment and 2) evidence supporting the positive conservation effects of alternative vegetation states. We have, therefore, separated our assessment into two components: 1) an evaluation of the direct benefits of recommended practices from the Range Planting CPS and 2) a brief review of specific conservation effects attributed to alternative vegetation states.

Assessment of the Direct Benefits of Range Planting Practices

The Range Planting CPS includes general recommendations for identification and utilization of site-appropriate plant materials, along with the use of soil preparation and planting techniques for optimization of seedbed microclimate.

Plant Materials Development and Selection

The Range Planting CPS recommends selection of plant materials that are adapted to both climate and microclimate as affected by soil type, landscape position, and range-site characteristics. Gross climatic variability generally determines the historical complement of native species at a site and the suitability of introduced plant materials (Shown et al. 1969; Shiflet, 1994; Barbour and Billings 2000; Vogel et al. 2005; Natural Resources Conservation Service 2006¹). The general importance of climate is acknowledged in seeding guides in the form of tables that list species and cultivar suitability as a function of mean annual precipitation (Jordan 1981; Jensen et al. 2001; Lambert 2005; Ogle et al. 2008a, 2008b; Bower et al. 2014). Seeding guides may also cite climatic thresholds below which active seeding practices are not recommended (Anderson et al. 1957; Jordan 1981).

Plant material recommendations for both native and introduced species are based primarily on plant materials discovery, screening, and breeding programs by NRCS Plant Materials Centers and other government research and agricultural experiment station programs (Roundy and Call 1988; Asay et al. 2003²). Native plant populations that have been identified as possessing superior productivity, vigor, establishment, disease resistance and/or seed-production characteristics, or alternatively have been bred for such traits, are then evaluated and released for commercial use (Schwendiman 1958; Johnson and Asay 1995; Jensen et al. 2001; Asay et al. 2003; Jones et al. 2004a, 2004b; Jones 2010; Robins et al. 2013³). More recent efforts in plant material development and evaluation focus on selection for, or comparison of, specific ecological and physiological traits (Aguirre and Johnson, 1991a, 1991b; Johnson and Asay 1995; Arredondo et al. 1998; Jensen et al. 2005; Parsons et al. 2011; Leger and Baughman 2015⁴). These efforts incorporate and report detailed experimental design information but are often based on relatively controlled experimental conditions in the laboratory and greenhouse or an agricultural field environment (Arredondo et al. 1998; Jones et al. 2010⁵). The majority of current plant material recommendations, however, are based on evaluations of field performance that are not accessible through refereed journal publications (Jensen et al. 2001; Lambert 2005; Ogle et al. 2008a, 2008b⁶). In order to be more effective, future plant materials need to be ecologically appropriate for the site (Jones 2013), especially if the site has converted to a novel ecosystem (Jones et al. 2015). Seeding prescriptive genetic diversity to the site to assist natural evolutionary processes has been termed “assisted evolution” (Jones and Monaco 2009). In some cases, it may be advantageous to intentionally develop such material by practicing artificial selection (Chivers et al. 2016) for functional traits that contribute to ecological fitness (Jones et al. 2010).

Seedbed Preparation and Planting Methods

Seedbed preparation and planting methods are designed to optimize microclimatic conditions for planted species, to increase the number of favorable microsites for germination and establishment, and to mitigate or control competition from undesirable species (Call and Roundy 1991; Sheley et al., 1996, 2006; Roundy and Call 1988; Krueger-Mangold et al. 2006).

Surface Modification

Soil-surface modification is often justified by expectations of increased water availability to the seed, either by improving seed–soil contact, reducing the amount of surface area subject to evaporation, increasing infiltration and water-holding capacity, or creating specific microsites that either receive or retain water more effectively (McGinnies 1959; Roundy et al., 1992; Madsen et al. 2015⁷). In some situations, cultivation without surface firming can increase the surface area subject to evaporation, reduce effective seed–soil contact, reduce seeding depth control, decrease hydraulic conductivity from deeper soil layers, and stimulate weed establishment if seeds are not effectively buried (McGinnies 1962; Kyle et al. 2007; Boyd and Obradovich 2014). Subsequent soil firming from press wheels or cultipackers improves hydraulic conductivity to the seed by reducing soil surface area and soil macroporosity (Hyder and Sneva 1956; McGinnies 1962). The bulk of the range planting literature does not separate treatment effects of soil firming from effects of specific cultivation and planting procedures, which are usually performed together (Bement et al. 1965; McGinnies 1972; Slayback and Renney 1972). Studies that compare multiple seed-bed preparation methodologies often find differences in relative seeding success with different equipment and techniques, but specific inferences can only be made at the treatment level for a given site and year (Hubbard and Smoliak 1953; Hyder et al. 1955⁸). Few studies of this type have been replicated adequately in multiple years or on multiple sites (Bement et al. 1965; Eckert and Evans 1967; Klomp and Hull 1972; Wood et al. 1982; Young et al. 1990; Bakker et al. 2003).

Animal trampling, land imprinting, pitting, furrowing, and rolling treatments have all been used in conjunction with broadcasting to capture or preserve moisture and to press surface-applied seed into the soil (Ethridge et al. 1997; Roundy et al. 1992⁹). Animal ingestion and subsequent deposition of seeds in dung has also been used as a mechanism to disperse seeds into favorable microsites (Akbar et al. 1995; Andrews 1995; Auman et al. 1998; Gokbulak and Call 2004; Kronberg 2015; Ocumpaugh et al. 1996; Traba et al. 2003). Differential establishment success relative to position of soil surface features has been reported and is generally attributed to differences in fine-scale microclimatic conditions (Anderson and Swanson 1949; Hyder and Sneva 1956; McGinnies 1959; Hull 1970; Bragg and Stephens 1979; Hauser 1982; Eckert et al. 1986; Roundy et al. 1992). Surface-modification treatments, however, have also been reported to push small seeds too far into the soil or to cause surface features to fill with soil from wind and water erosion, resulting in seed burial exceeding optimal establishment depth (Hyder and Sneva 1956; Kincaid and Williams 1966; McGinnies 1972; Slayback and Renney 1972; Winkel et al. 1991a).

Positive effects of soil-surface modification may be less relevant in very wet years when water is generally available, regardless of surface treatment, or in very dry years when plantings are unsuccessful regardless of seedbed preparation technique (McGinnies 1968; Stuth and Dahl 1974; Wood et al. 1982; Eckert et al. 1986; Roundy et al. 1990, 1992; Winkel and Roundy 1991; Romo and Grilz 2002).

Mulch Application

Application of mulch is frequently advocated as a mechanism to reduce water loss and moderate soil-surface temperatures, although with the caveat that it is probably not cost-effective for most rangeland applications (Lavin et al. 1981; McGinnies 1987; Ethridge et al. 1997; Young et al. 2013). Relatively expensive soil surface amendments are generally applied only after high-impact disturbance such as mine reclamation or

for mitigation of erosion after wildfire on topographically complex terrain (Schuman et al. 1985; Groen and Woods 2008¹⁰). An exception may be mulch production as a by-product of mechanical shredding for control of juniper and other woody species (Brockway et al. 2002; Stoddard et al. 2008). Establishment of a cover crop to create standing-stubble mulch is usually limited to relatively small areas of major disturbance or higher precipitation zones where grazing lands are being reclaimed from cultivation (Stroh and Sundberg 1971; Stubbendieck et al. 1973; Pinchak et al. 1985; Schuman et al. 1985; Hart and Dean 1986). Justification for mulching practices has been primarily derived from greenhouse, laboratory, and modeling studies, all of which confirm general benefits of water conservation and mitigation of high temperatures near the soil surface (Chung and Horton 1987; Novak et al. 2000¹¹), as well as field studies, most of which have been conducted after tillage or on severely disturbed, or otherwise extreme, sites (Schuman et al. 1985; Groen and Woods 2008¹¹). Water conservation associated with mulch application may not be ecologically significant in very high or very low precipitation years or on some extreme rangeland sites (Gates 1962; Ludwig and McGinnies 1978; Lavin et al. 1981; Berg and Sims 1984; McGinnies 1987; Bristow 1988; Cione et al. 2002; Fulbright et al. 2006). Regardless of the variable effects of mulch on seeding success per se, the positive effect of mulch for erosion control and soil stabilization is well documented (Meyer et al. 1970; Bautista et al. 1996; Fulbright et al. 2006; Groen and Woods 2008; Stoddard et al. 2008).

Seeding Depth

Successful germination and establishment depend on placement of seeds in favorable soil microsites (Call and Roundy 1991; Roundy et al. 1992; Chambers and MacMahon 1994¹²). A major assumption of many site-preparation treatments is that they increase the number of potential safe sites for germination and establishment by covering the seed, reducing soil-water loss from around the seed, or redistributing and concentrating resources (Anderson and Swanson 1949; Hubbard and Smoliak 1953¹³).

Mechanical disturbance is generally necessary to incorporate seeds into the soil, thus reducing the risk of either desiccation or adverse thermal effects near the surface. Seeding-depth recommendations from commonly cited seeding guides and technical references are relatively specific, but they are based on rules of thumb regarding seeding depth as a function of seed size (Plummer et al. 1968; Roundy and Call 1988; Monsen and Stevens 2004¹⁴). The physical rationale for depth recommendations usually assumes a trade-off between increased water availability and increased energy requirements for emergence as a function of depth (Call and Roundy 1991; Roundy and Call 1988¹⁵). In some cases, light or diurnal temperature fluctuation may regulate dormancy to ensure that the seeds germinate at an appropriate depth for a given species (Call and Roundy 1991; Ghera et al. 1992; Traba et al. 2004). Seed predation has also been documented as a potential problem for surface-sown seeds (Nelson et al. 1970; Longland and Ostojka 2013; Gurney et al. 2015).

Evidence for depth effects is generally limited to studies conducted in a controlled environment, or over very small spatial scales in the field (Kinsinger 1962; Vogel 1963; Hull 1964¹⁶). A major exception is for studies comparing the relative establishment of broadcast versus planted seeds. The majority of range seeding studies conclude that drill seeding outperforms broadcast seeding, although there is generally no quantification of the specific depth distribution of seeds after planting (Haferkamp et al. 1987; Ott et al. 2003; Davies et al. 2013; Bernstein et al., 2014; Knutson et al. 2014¹⁷). Relative seeding depth in field studies is often reported only in the context of depth band settings on mechanical seeding equipment, but there are very few studies in which actual seeding depth has been quantified post planting (Winkel and Roundy 1991; Winkel et al. 1991a, 1991b). Laboratory, greenhouse, and field comparisons of surface-sown versus planted seeds generally confirm that very small seeds establish more frequently from near-surface seed placement, larger seeds require soil cover for maximal performance, and seed performance drops dramatically

below some threshold depth (Hull 1948; Stewart 1950; Douglas et al. 1960¹⁸). Indian ricegrass (*Achnatherum hymenoides* [Roem. & Schulte.] Barkworth) has been extensively documented for its ability to germinate and emerge from relatively deep sowing depths, especially in sandy soils (Kinsinger 1962; Jones 1990; Young et al. 1994). Broadcast and planting recommendations are generally not discretionary, as topographic complexity and economic considerations may preclude the use of planting equipment.

Seeding Rate

General seeding-rate recommendations from many technical sources appear to be based on a general standard for what could be considered a hypothetical dominant bunchgrass, planted at optimal depth in a uniform, well-prepared, weed-free seed bed in a favorable establishment year. The standard seeding rate for this hypothetical scenario seems to be roughly equal to a seed density of 1 million seeds per acre or approximately 23 seeds/ft² under historical, non-SI units of measure (Jordan 1981; Jensen et al. 2001; Monsen and Stevens 2004; Lambert 2005; Ogle et al. 2008a, 2008b). The most commonly recommended deviation from this hypothetical standard is to increase seeding rate by a factor of 2 to 5 for small seeds or for potential location-specific problems such as inadequate weed control, lack of site preparation, surface application of seeds, probability of drought, nonoptimal seeding season, or high levels of seed dormancy (Jordan 1981; Monsen and Stevens 2004; Thompson et al. 2006). Broadcast seeding rates are generally recommended at two to three times the rates for seed that can be incorporated into the soil (Haferkamp et al. 1987; Ott et al. 2003¹⁹). Seeding-rate recommendations are also generally adjusted to reflect the total seed-mix ratio and ideal expectations for composition of the desired mature-plant community (Pyke and Archer 1991; Ogle et al. 2008a, 2008b). It is often difficult to assess numerical seeding rates, as the bulk of the literature reports rate in terms of weight of seed planted per unit land area. Weight-based recommendations in the technical literature, however, are generally supplemented by bulk seed density information (Plummer et al. 1968; Jensen et al. 2001; Monsen and Stevens 2004; Lambert 2005; Ogle et al. 2008a, 2008b).

Seeding-rate recommendations are linked to microclimatic considerations, as increased seed numbers increase the probability of seeds reaching safe microsites, irrespective of active depth management (Call and Roundy 1991; Chambers 1995; Harper et al. 1965; Roundy et al. 1992). Relatively few studies reporting effects of seeding rate on establishment success are replicated in such a way to survey annual and seasonal variability in seed-bed microclimate (Masters 1997; McMurray et al. 1997; Williams et al. 2002²⁰). Some studies that include variable seeding rates were primarily designed to evaluate competition relative to weed-seed numbers, but in general, the literature supports the concept that higher seeding rates may enhance the likelihood of successful initial establishment (Vogel 1987; Sheley et al. 1999; Wiedemann and Cross 2000; Williams et al. 2002; Schantz et al. 2015).

Seeding-rate impacts remain highly dependent on threshold requirements for water availability in the early stages of establishment, and individual seedling growth can be negatively impacted by both interspecific and intraspecific competition later in development. The majority of the literature pertaining to seeding-rate effects is derived from either controlled environment and greenhouse studies or field studies conducted in years where reported rainfall conditions were either average or above average (Francis and Pyke 1996; Sheley and Half 2006). Eiswerth and Shonkwiler (2006) evaluated a large number of range seeding sites and years in Nevada and determined that increased seeding rates led to higher seedling densities for non-native grasses up to some maximum seeding rate. This study, however, did not analyze or report negative seeding results and did not consider weather and climate conditions during the years that seeding occurred. Eiswerth et al. (2009) evaluated a longer-term field dataset and found less evidence for seeding-rate effects on perennial grasses, but they confirmed benefits of higher seeding rates for planted forbs.

Planting Season

Most studies of planting-season effects on establishment success can be linked to climatic variability and often to specific germination and dormancy syndromes of various seeded, nonseeded, and weedy species (Angevine and Chabot 1979). General planting-season recommendations suggest planting to take advantage of the most favorable season for plant establishment (Stoddart and Smith 1955; Plummer et al. 1968; Vallentine 1979; Roundy and Call 1988; Monsen and Stevens 2004²¹). In some cases, fall seeding is recommended well in advance of the optimal growing season to accrue all potential establishment benefits in a highly variable and often arid or semiarid environment (Plummer et al. 1968 et al.; Monsen and Stevens 2004; Boyd and Lemos 2015²¹). Recent studies suggest that many planted species can be expected to exhibit high fall germination and that a principal bottleneck for early plant establishment may be postgermination, pre-emergence mortality during winter (James et al. 2011, 2012; Boyd and James 2013; Boyd and Lemos 2013, 2015; Gornish et al. 2015; Hardegree et al. 2016). Fall seeding, however, is often recommended to avoid use of mechanical planting equipment under wet-spring conditions or to mitigate effects of unpredictable spring weather (Stewart 1950; Douglas et al. 1960; McGinnies 1973; Hart and Dean 1986; Boyd and Lemos 2015). Seasonal timing of seeding may also be dependent on seasonality of weed competition and/or optimal timing of weed control measures (Bement et al. 1965; Robocker et al. 1965; Hull 1972; Klomp and Hull 1972; Schantz et al. 2015).

The most favorable season for establishment varies regionally (Hatfield 1990): spring in Mediterranean-coastal and Intermountain West locations (Douglas et al. 1960; Nord et al. 1971; Hull 1972; Harris and Dobrowolski 1986), summer monsoon in the southwestern desert (Jordan 1981; Abbott and Roundy 2003; Hereford et al. 2006), late spring through early summer in the Great Plains (Robertson and Box 1969; Hyder et al. 1971; McGinnies 1973; Hart and Dean 1986; Ries and Hofmann 1996; Frank et al. 1998; Romo and Grilz 2002), and late spring through early fall in some higher-elevation mountain sites (Hull 1966, 1974; Currie 1967; Lavin et al. 1973). Postplanting microclimate must be favorable for growth, but it also needs to remain favorable during the vulnerable period of seedling establishment (Hyder et al. 1971; McGinnies 1973; Frasier et al. 1987; Abbott and Roundy 2003). Eiswerth and Shonkwiler (2006) confirmed the relative benefits of fall/winter seeding on Intermountain rangelands in Nevada with the use of meta-analysis of long-term Bureau of Land Management (BLM) fire-rehabilitation monitoring data. Very few experimental studies of seeding-season effects, however, are replicated in more than 1 or 2 years (Hull 1948, 1974; Douglas et al. 1960; Robocker et al. 1965; Ries and Hofmann 1996; Boyd and Lemos 2015).

Weed Control

Seed bed preparation and planting method recommendations are designed to improve microclimatic conditions for desirable species, but also to reduce competition from undesirable plants (Lavin et al. 1973; Gonzalez and Dodd 1979; Ott et al. 2003; Mangold et al. 2007). Chemical or mechanical weed control, before the early stages of establishment, are generally recommended for establishment success of both native and non-native plant species (Evans et al. 1970; Nelson et al. 1970; Klomp and Hull 1972; Stuth and Dahl 1974; Evans and Young 1978; Humphrey and Schupp 2002; Mangold et al. 2007; Davies 2010; Davies et al. 2015; Sheley et al. 2012; Kyser et al. 2013; James et al. 2015). Of the various studies surveyed in this review that included mechanical or chemical weed control, the majority concluded that weed control was either necessary or at least beneficial for successful establishment. Weed competition effects, however, may not dominate depending on the relative degree of abiotic stress (Mangla et al. 2011) and weed-control strategies may require replication over the longer term to be effective (Davies et al. 2015).

Assessment of Specific Conservation Effects

Evidence supporting positive conservation effects of alternative, established plant communities is generally found in a separate body of

literature than that examined in the previous section of this paper. The literature supports the concept that seeding, if successful, results in positive conservation effects. There are relatively few studies, however, directly linking rangeland seeding to conservation effects. We have limited our review to conservation effects related to water quality and erosion, water quantity, and soil-carbon sequestration as successful rangeland seeding has previously been primarily defined by metrics associated with increased biomass availability as forage.

Water Quality and Erosion

Very few studies directly link rangeland seeding to conservation benefits from improved water quality and reduced erosion (Wright et al. 1982; Brown et al. 1985; Beyers 2004; Pierson et al. 2007b; Pierson et al. 2010; Petersen and Stringham 2008; Miller et al. 2012; Royer et al. 2012; Roundy et al. 2014). There is an extensive literature, however, documenting the relationship between rangeland soil cover and soil stability (Nearing et al. 2005; Bartley et al. 2006; Gimeno-Garcia et al. 2007; Pierson et al. 2010²²). Removal of plant-canopy cover by clipping may be insufficient to increase sediment loss in the short term when soil is still protected by basal vegetation cover and surface residues (Giordanengo et al. 2003; Gysels et al. 2005; Nearing et al. 2005; De Baets et al. 2006). Range planting per se will not have a significant effect on soil stability unless sufficiently successful to provide adequate soil cover (Meeuwig 1965; Gifford 1970, 1972; Wright et al. 1982; Brown et al. 1985; Ziegler and Giambelluca 1998; Aguilera et al. 2003; Beyers 2004; Groen and Woods, 2008; Pierson et al. 2010). Short-term effects of site preparation, fire, or other treatments that precede range seeding or natural recovery, however, can significantly increase potential erosion in the near term (Gimeno-Garcia et al. 2007; Grismer 2007; Pierson et al. 2007a, 2007b; Miller et al. 2012²³). In most cases, the nature of this cover is less relevant than the issue of soil-surface protection above some threshold level (Aguilera et al. 2003; Mergen et al. 2001; Descheemaeker et al. 2006²⁴). Some studies, however, have shown differential hydrologic effects in adjacent plant communities due to differences in growth and litter production, rainfall interception, water-use efficiency, or rooting depth and spread (Dunkerley 2002; Bhark and Small 2003; Kulmatiski et al. 2006²⁵). The relative impact of vegetation cover on erosion and runoff is also highly dependent on weather, slope, and soil type (Aguilera et al. 2003; Bartley et al. 2006; Nichols 2006²⁶). Major soil loss after vegetation removal can be exacerbated by intense rainfall events (Gifford 1973, 1975; Garza and Blackburn 1985; Takar et al. 1990).

Vegetation affects soil stability and runoff water quality by protecting the soil from rainfall impact, increasing soil infiltration capacity, anchoring the soil mass, and preventing the development of rill erosion by slowing overland flow rates and increasing surface — water flow paths (Tromble et al. 1974; Thurow et al. 1987; Pimentel and Kounang 1998; Aguilera et al. 2003; Imeson and Prinsen 2004; Puigdefabregas 2005). Invasive woody plants have been shown to suppress understory species to the point where insufficient soil-surface cover can result in significant erosion, even under relatively low-intensity storm events (Davenport et al. 1998; Pierson et al. 2007a, Pierson et al. 2010; Petersen and Stringham 2008). Annual-weed cover can affect seasonal patterns of evapotranspiration and soil-water use (Kulmatiski et al. 2006; Prater and DeLucia 2006), but there is little evidence that they increase site runoff or erodibility when they are providing adequate soil cover (Singh 1969; Pierson et al. 2002, 2007b; Wilcox and Thurow 2006; Miller et al. 2012). In the Intermountain West, however, invasive annual weeds can increase the frequency of periods where vegetation cover can be reduced by wildfire (Brandt and Rickard 1994; Knapp 1996; Young and Longland 1996; Whisenant 1999; Pierson et al. 2011). Indeed, the primary objective of most fire-rehabilitation seeding practices is to improve soil stability and reduce erosion (Richards et al. 1998; Beyers 2004; BLM 2007; Grismer 2007).

Application of mulch to improve range-planting success is probably not cost-effective for most rangeland applications (Lavin et al. 1981; McGinnies 1987; Ethridge et al. 1997). Mulch application, litter retention after site preparation, and mulch production as a result of mechanical treatments for woody plant control, however, can have a direct conservation effect of reducing erosion and runoff on severely disturbed or highly erodible range sites or on steep slopes (Fulbright et al. 2006; Groen and Woods 2008; Stoddard et al. 2008; Cline et al. 2010; Pierson et al. 2014²⁷).

Water Quantity

Different plant materials and species may have different degrees of water-use efficiency and biomass production, but in arid rangeland systems, plants tend to use all of the available water in the soil profile in most years (Wilcox 2002; Huxman et al. 2005; Wilcox and Thurow 2006; Moore et al. 2012²⁸). Seeding grasses after shrub removal can result in increased stream flow in some Mediterranean-type climates, where the principal precipitation season is out of phase with the seasonal peak of evapotranspiration, or in systems where woody plant material has access to groundwater (Hill and Rice 1963; Hibbert 1983; Huxman et al. 2005; Wilcox 2002; Huang et al. 2006; Wilcox and Thurow 2006). Shrubland conversion to grassland is not generally expected to result in an increase in water quantity in arid and semiarid upland rangeland systems, except where vegetation removal may increase overland flow directly to a stream channel (Gifford 1970; Wright et al. 1982; Bergkamp 1998; Wilcox 2002; Wilcox et al. 2003; Wilcox and Thurow 2006) or during extreme rainfall events where runoff may be affected by total plant cover (Weltz and Blackburn 1995; Quinton et al. 1997). The major exception to this would be the relatively large potential increase in overland flow after major vegetation disturbance, which may also generate unacceptable levels of soil erosion (Gifford 1973; Osborn and Simanton 1990; Takar et al. 1990; Johansen et al. 2001; O'Dea and Guertin 2003; Pierson et al. 2007a, 2007b).

Carbon Sequestration

Svejcar et al. (2008) summarized the results of a 6-yr regional experiment that monitored seasonal carbon flux on western US rangelands and found that relatively good condition rangeland generally serves as a carbon sink, except in the driest areas of the Desert Southwest. The degree of carbon sequestration or loss varies primarily in response to seasonal and annual weather patterns (Conant et al. 2001; Flanagan et al. 2002; Jones and Donnelly 2004; Xu and Baldocchi, 2004; Follett and Schuman 2005; Hastings et al. 2005; Derner and Schuman 2007; Svejcar et al. 2008; Bremer and Ham 2010; Brown et al. 2010; Follett and Reed 2010; Gilmanov et al. 2010; Zhang et al. 2010). A change from tillage and annual cropping to perennial grass cover can greatly increase soil carbon sequestration rates, but the effect is less on western rangeland soils than in more mesic areas (Conant et al. 2001; Guo and Gifford 2002; Sperow et al. 2003; Jones and Donnelly 2004; Derner and Schuman 2007). Relatively low sequestration rates, however, are offset by the relatively large land area occupied by rangelands (Scurlock and Hall 1998; Derner and Schuman 2007; Brown et al. 2010; Follett and Reed 2010; Gilmanov et al. 2010). Type conversion from woody plants to grasses can lower carbon sequestration rates if the initial plant community has a higher net ecosystem production, but this would probably not be the case in most upland arid and semiarid rangeland systems (Huxman et al. 2005; Campbell et al. 2012). Restoration of severely disturbed rangeland and activities such as mine reclamation can significantly improve carbon sequestration rates (Follett and Schuman 2005; Derner and Schuman 2007).

Rooting depth and effective water utilization for biomass production can vary considerably among alternative vegetation types (Cline et al. 1977; Cable 1980; Yoder et al. 1998; Huxman et al. 2005; Seyfried and Wilcox 2006). As a significant portion of sequestered carbon can be

deposited below ground by root growth (Scurlock and Hall 1998; Jones and Donnelly 2004; Rees et al. 2005; Cleary et al. 2010), depth of rooting may be a consideration in selection of plant materials for rangeland seeding operations.

Millions of acres of sagebrush-bunchgrass rangeland in the Intermountain West have also been invaded by introduced annual weeds such as cheatgrass (*Bromus tectorum* L.) and medusahead wildrye (*Taeniatherum caput-medusae* [L.] Nevski). Annual weed-dominated systems are characterized by more frequent recurrence of wildfire and may resist management actions that are designed to return them to a more desirable ecological state (Brandt and Rickard 1994; Knapp 1996; Young and Longland 1996; Nafus and Davies 2014). Carbon-sequestration rates can be nullified when vegetation is periodically removed by prescribed fire or wildfire (Suyker and Verma 2001; Bremer and Ham 2010; Cleary et al. 2010).

Knowledge Gaps

Explicit Testing of New Conceptual Models for Dynamic Rangeland Systems

Call and Roundy (1991) recommended changes from the predominant site-specific, short-term, empirical-research approach to more directly address the underlying ecological processes driving restoration success and problems associated with high spatial and temporal variability in rangeland systems. A more general scientific understanding of vegetation change may now be achievable through adoption of conceptual models for understanding dynamic rangeland systems (Westoby et al. 1989; Bestelmeyer et al. 2003; Sheley et al. 2006). NRCS has already accepted this paradigm by incorporating state-and-transition-model concepts in the development of Ecological Site Descriptions, but these models are not explicitly incorporated into range planting conservation practice recommendations. These models integrate multiple processes and acknowledge multiple potential trajectories for plant community change and will require new and innovative approaches for validation and testing in the field.

Development and Utilization of Weather and Forecasting Tools

The stochastic nature of weather variability will require adoption of new concepts for evaluating revegetation and restoration success. Expectations for success need to be explicitly linked to the probability of favorable conditions for seed germination, emergence, and establishment (Krzysztofowicz 2001; Bakker et al. 2003). New technologies will need to be developed to use weather information to inform rangeland planting management decisions (Workman and Tanaka 1991; Peters 2000; Rayner et al. 2005; Andales et al. 2006; Hardegree et al. 2012a, 2012b).

The most useful potential technology for enhancing establishment success lies in development and utilization of seasonal weather-forecast technology specific to rangeland planting applications (Barnston et al. 1994, 2005; Garbrecht and Schneider 2007). Seasonal weather forecasts in large portions of the Intermountain West are often merely synoptic descriptions of historical weather patterns and are not based on physical or empirical prediction of future weather conditions. It may be possible, however, to utilize historical weather and seeding data to construct models to assess the potential long-term benefits of adopting forecast/modeling technology in rangeland restoration planning (Batabyal and Godfrey 2002; Schneider and Garbrecht 2003, 2006; Bashari et al. 2008; Hardegree et al. 2013). Similar technology is in relatively common use for more traditional agricultural applications and for some rangeland applications (Schneider and Garbrecht 2003, 2006; Doblas-Reyes et al. 2006; Baigorria et al. 2008; O'Lenic et al. 2008).

Even low-resolution seasonal weather forecasts would increase the probability of successful native plant establishment if seeding decisions in the fall could be based on the anticipation of favorable conditions of seedbed microclimate in the subsequent winter and spring (Hardegree et al. 2003; Hardegree and Van Vactor 2004). Weather

forecasts could be used to initiate contingency plans in areas that have been previously identified for restoration, and for which premanagement logistics of equipment, personnel, and plant materials are in place (Westoby et al. 1989; Bakker et al. 2003). Separation of restoration planning objectives from the wildfire cycle would also simplify the problem of predicting management needs for native germplasm (Richards et al. 1998). Historical climate records could provide a relatively stable estimate of the probability of favorable establishment years that could be used to predict acquisition and storage requirements for native seed over the long term.

Biodiversity and restoration planning objectives may require multiple-year strategies for replacement of non-native species only after initial site stabilization and suppression of annual weed competition (Bakker et al. 2003; Cox and Anderson 2004). Weather and climatic limitations require definition of realistic goals when establishing rehabilitation and restoration planning objectives (Call and Roundy 1991; Hobbs and Norton 1996; Ehrenfeld 2000; Jones 2003). Asay et al. (2001) argue that the relatively harsh climatic conditions on many rangelands may preclude the realistic use of many native plant materials in favor of adapted non-native species. In some years, and on some sites, it may be prudent to plant more easily established non-native species, particularly after wildfire or other disturbance, when the principal objective of rangeland planting may be soil stabilization. Biodiversity and restoration objectives could then be addressed in years when climatic conditions are amenable (Holmgren and Scheffer 2001; Bakker et al. 2003; Hardegee et al. 2003; Cox and Anderson 2004; Hardegee and Van Vactor 2004). Seasonal weather forecasts would perhaps improve the probability of successful native establishment if planting were limited to years with a favorable prediction for establishment success.

Plant Materials Program Development and Testing

Previous plant materials development has focused on productivity, vigor, establishment, disease resistance, seed production, and specific ecological and physiological traits deemed to confer superior performance or adaptation. Establishment, persistence, and invasion resistance of seeded plant communities may be enhanced by identification and selection of plant materials with functional traits similar to the various highly competitive invasive species (Arredondo et al. 1998; Pokorny et al. 2005; Funk et al. 2008; Leger and Espeland 2010; Steers et al. 2011; Leger et al. 2014). Functional traits common to many weedy invaders include high relative growth rate, specific leaf area, leaf nitrogen content, and resource-use efficiency (Aguirre and Johnson 1991a, 1991b; Grotkopp et al. 2002; Pokorny et al. 2005; Grotkopp and Rejmanek 2007; James and Drenovsky 2007; Funk et al. 2008; Larson et al. 2015, 2016). This type of functional trait selection, however, may only confer advantages in early seral stages of plant community development. We still need to improve our understanding of abiotic thresholds for plant establishment and persistence at all stages of succession, regardless of the suite of functional traits exhibited (Roundy et al. 1993, 1997; Biedenbender and Roundy 1996; Abbott and Roundy, 2003).

Development of herbicide-resistant native grass plant materials may be a useful area of future research. In recent years, interest has increased in using acetolactate synthase (ALS) inhibitors such as Imazapic to reduce annual grass competition with desirable perennials (Davies 2010; Hendrickson and Lund 2010; Elseroad and Rudd 2011; Hirsch et al. 2012; Kyser et al. 2012, 2013; Sheley et al. 2012). Imazapic damages fast-growing tissues, especially meristems, so weedy annual grasses and crucifers are controlled with less damage to perennials (Shaner and O'Conner 1991). Some residual activity is present, so annual grass control is still achieved a year following application (Davison and Smith 2007). An advantage of this herbicide is that many desirable nongrass species, particularly legumes and composites, are relatively resistant. Development of ALS-inhibitor resistance has been quite successful in several crop species (Tranel and Wright 2002); thus development

of native plant materials with such resistance is likely to be successful. When such materials are developed by traditional plant-breeding methodologies, no special Environmental Protection Agency clearance is required before release.

For many years, the NRCS, US Forest Service, and Agricultural Research Service have routinely evaluated and released experimental materials as part of their ongoing plant-material research and development programs (Roundy and Call 1988; Alderson and Sharpe 1994; Asay et al. 2003). Comparisons between plant species and among plant materials within species are made in order to characterize released plant materials and to justify the release of new plant materials (Jensen et al. 2001; Lambert 2005; Ogle et al. 2008a, 2008b). These trials are typically replicated complete block design experiments subject to statistical analysis, but they are usually analyzed as individual experiments rather than as a collective whole. Because these trials are conducted every year, a large volume of data has been collected. More robust comparisons of species and plant materials could be made if these data were compiled and subjected to meta-analysis.

Adoption of Standard Protocols for Evaluating Success and Development of Meta-Analysis of Field Trials

The majority of range planting studies do not measure critical environmental factors affecting success but only measure relative treatment effects (Call and Roundy 1991; Vargas et al. 2001). Range planting studies also tend to extrapolate results obtained from atypical sites and conditions over larger areas (Cox et al. 1984) and are seldom replicated in multiple seeding years (Casler 1999). Generally, high variability in experimental procedures often produces unique individual studies from a complex combination of unique site preparation, plant materials, seeding rate, soil conditions, and weather during only 1 or 2 establishment years. An important recommendation is adoption of minimum experimental design requirements for publication of range planting studies relative to specific inferences that are of principal interest (Casler 1999; Vargas et al. 2001).

Success metrics are highly variable and often consist of relative ranking of treatment effects, and there has been little research to evaluate alternative criteria for quantification of success (Ries and Svejcar 1991). The majority of range planting studies only consider treatment effects in the first year after planting, and studies that are monitored for longer periods are generally not replicated for planting-year effects (Casler 1999). Many studies that have monitored range planting results in the very long term have noted significant changes from what would have been measured only 1–3 years post planting (Bleak et al. 1965; Hull 1971, 1973; Lavin and Johnson 1977; Eck and Sims 1984; Harris and Dobrowolski 1986).

In general, most individual studies within the range planting literature are insufficiently replicated to extract valid inferences about weather and climate effects, site effects, plant-materials effects, and seeding rate. The dominant level for validation in the currently available literature derives from interspersed and within-location replication of seedbed preparation treatments. These studies, as well as a large amount of data contained in conference proceedings, technical reports, and internal-agency documents, might be subject to valuable meta-analysis of treatment effects that are difficult or impossible to replicate in the context of a stand-alone journal publication (Durlak and Lipsay 1991; Gurevitch et al. 1992, 2001; Adams et al. 1997; Michener 1997; Gurevitch and Hedges 1999; Osenberg et al., 1999a, 1999b; Johnson 2006). Much of this information may only be suitable for low-level meta-analysis to document gross treatment effects. It may be possible, however, to develop guidelines for establishing some common experimental design features for future studies that may be amenable to more sophisticated meta-analysis.

Another underutilized research resource is the incorporation of extensive management-level monitoring information into a scientific database format (Pastorok et al. 1997). Eiswerth and Shonkwiler (2006)

used a BLM data set to evaluate postfire management treatment effects on seeded non-native grasses, sagebrush, and annual weeds as a function of range site, soil type, and seeding prescription. Unfortunately, this data set did not evaluate impacts of weather and climate variability. More recently, BLM management data contained in the Land Treatment Digital Library have been used to conduct meta-analysis of treatment effects on postfire emergency stabilization and rehabilitation across multiple years and sites in the Great Basin (Gray and Muir 2013; Sankey et al. 2013; Arkle et al. 2014; Knutson et al. 2014; Leger and Baughman 2015). Effective utilization of these data may also require some degree of coordination within and between management agencies to adopt similar monitoring protocols. NRCS Conservation Practice Standards could be improved by establishing standard monitoring requirements to assess both the effectiveness of specific management recommendations and conservation effects of successful practices. Monitoring requirements, however, should be based on an explicit experimental design that would facilitate future meta-analysis.

Recommendations

The aggregate literature generally supports both the existing conservation practice recommendations for rangeland seeding and the inherent assumption that if these practices are successful, they will result in beneficial conservation effects. Current conservation practice recommendations, however, are relatively prescriptive in that they do not effectively address site- and year-specific variability, provide no mechanism for evaluating or adapting to unsuccessful or partially successful treatments, are oriented toward short-term management, and are not fully integrated with current ecologically based models for management of alternative vegetation states. Current conservation-practice standards could be improved with references to more ecologically based technical literature and by providing specific guidance for both monitoring and adaptive management in rangelands with an inherently high level of annual and seasonal weather variability.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.rama.2016.04.007>.

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