Effects of Summer Weather Modification (Irrigation) in *Festuca Idahoensis-Agropyron spicatum* Grasslands

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Highlight: A simulated summer cloud seeding program was conducted for 4 years on a *Festuca idahoensis-Agropyron spicatum* grassland. Production and phenologic responses were essentially nil when plots were given 1.1, 1.2, 1.4 times natural rainfall on a per storm basis by sprinkler irrigation. Watering at the rate of 5 cm/week extended the flowering period in only one species, *Tragopogon dubius*; extended the green leaf season in most species; and increased the production of only three species, *Festuca idahoensis*, *Balsamorhiza sagittata*, and *Tragopogon dubius*. The increased production occurred only in the year following irrigation and may have been due to increased plant reserves and vigor. It appears that summer cloud seeding programs will have little or no positive effect on production in this vegetation type.

Precipitation can probably be increased in the Northern Great Plains of the United States by cloud seeding. Silver iodide seeding has increased the yield from specific cumulus clouds in many experiments and seasonal increases of 10–20% have been suggested (National Research Council 1973; American Meterological Society 1970; Battan 1969). Within the Great Plains, the potential for increasing precipitation may be greatest in the northern high plains area (Weinstein 1972).

The long-term effects of precipitation increases on native grasslands, the dominant ecosystems of the Northern Plains, should be a conversion to the successfully functioning and generally more productive ecosystems found in areas to the east with similar temperatures and a similar seasonal distribution of precipitation, but higher precipitation. Similar conversions occurred in 10–20 years after the droughts of the mid-1930's and mid-1950's (Weaver 1968; Coupland 1958). The migration westward of more mesic species to fill sites created by artificially increasing precipitation will probably take more tnan 10–20 years (1) because propagules will not be as available on these sites as they were on sites "cleared" for short periods by drought and (2) because migration of propagules from source areas to the east will be hindered by large areas of intervening farmed land (Whittaker 1967). In their westward migration, eastern grassland ecosystems may be modified significantly if they migrate into environments different from those they presently occupy, i.e., if increases in precipitation are linked to shifts in the seasonal distribution of precipitation (Lewis 1970); to changes in the frequency of fire (= lightning, Daubenmire 1968); to changes in the frequency of hail (National Research Council 1973; American Meterological Society 1970); or to the effects of seeding agents (Weaver and Klarich 1973; White 1973; Teller and Cameron 1973; Klein and Molise 1975).

Because range composition is likely to change slowly, one also asks about the effects of weather modification on vegetation presently existing in the target area. The experiment described below was designed to answer such questions about short- and mid-term effects through simulated cloud seeding. In it we compared the performance of native bunchgrass vegetation on a plot receiving natural summer rainfall to the performance of bunchgrass vegetation on three adjacent plots receiving 1.1, 1.2, and 1.4 times natural rainfall on an individual storm basis. Appropriate additions were made immediately after each storm throughout the growing season. To determine the maximum possible effects of a precipitation management program we also observed the performance of vegetation in a constantly wet plot (soil water stress always kept below 2 bars). Four assumptions underlie our experiment. Even after successful cloud seeding, precipitation will still be within the normal range of precipitation; growing season precipitation in the northern plains averages less than 250 mm (USDA 1941) so increases are unlikely to exceed 50 mm (20%, see paragraph 1). Increases are likely to come as small additions to existing showers. The seasonal distribution of precipitation is unlikely to change since air masses suitable for seeding are unlikely to appear in drought seasons. And the probability of drought is unlikely to change, since air masses suitable for seeding are unlikely to appear in drought years (Borchert 1950).

Methods

The experiment was conducted in the *Festuca idahoensis-Agropyron spicatum* habitat type of Daubenmire (1970) and Mueggler and Handl (1974). The site was located 9.5 km north of Bozeman, Mont., on Bridger gravelly loam soils (DeYoung and Smith 1931). It has received little or no grazing for many years and its condition might be classed as "low good." Plant names used follow Hitchcock and Cronquist (1973).

In 1969 five 61 × 61 m (0.40 ha = 1 acre) plots were established in a relatively homogeneous area. The treatments imposed were, from east to west, 0%, 40%, 20%, 10%, and 5% supplements to natural rainfall. Due to lack of plant response in

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1969 and 1970 the 5% plot was converted in 1971 to a "continuously wet" plot in which irrigations of approximately 2.5 cm were made at 3-day intervals. Sprinkling began May 15, 1969, May 15, 1970, June 28, 1971, and June 15, 1972; it ceased on September 1 in all years. Sprinkling was postponed until mid-June in 1971–1972 because it was assumed that cloud seeding would be avoided during May and early June when the water content of soils is near field capacity. Actual additions made in 1969 were 0, 4, 9, 16, and 33% of the precipitation falling at the site (Table 1) with the deficiencies all in the unusually wet June. Additions in 1970 were 0, 4, 10, 20, and 39% of actual precipitation (Table 1). Additions in 1971 followed the same pattern but were nil—except in the constantly wet plot—because the June precipitation fell before sprinkling began and the July-August precipitation fell in showers too light to mimic (Table 1). Additions made in 1972 were 0, constantly wet, 12, 22, and 41% of actual precipitation. Supplements in the wet plot (formerly 5%) were 544 mm in 1971 and 458 mm in 1972. Supplemental water was added during evenings following showers to minimize evaporative losses. Additions to each plot were made with 28 "Rainbird" sprinklers on 45-cm risers. To provide natural drop sizes and good control of the amount of water applied, we used 11/64-inch nozzles in the wet and 40% treatment areas and ⅛-inch nozzles in the 20% and 10% areas.

Meterological conditions in the 1969–1970 period are compared with long-term averages in Table 1. Relatively large temperature deviations (exceeding 2°C) occurred in June 1970, August 1970, August 1971, and June 1972. Relatively large precipitation deviations (exceeding 50 mm) occurred in June 1969 and July 1970.

The effectiveness of the precipitation was determined by measuring the soil moisture at five sites in each treatment plot with plaster blocks (Taylor et al. 1961) and a "Coleman" meter at weekly intervals. At each site, blocks were buried at depths of 10, 25, and 75 cm.

Phenologic stages of important species were recorded weekly to determine whether plant development was affected by additional precipitation. Observations were made in 1 × 10-m subplots located near the center of each area treated. Control phenology plots were established in the unirrigated area and in the five unsprinkled buffer areas between the sprinkled plots. All phenological observations reported were made by one observer, L. Taylor. Grasses entered the flowering stage when the flower was "in the boot," entered the fruiting stage when the seed was hard, and entered the ripe stage when the seed was shed. For *Tragopogon dubius* the fruiting period is reported instead of the flowering period because fruiting is less ephemeral and therefore more dependable; the two periods are almost identical.

In each treatment area ten 0.5 × 1-m plots were clipped fortnightly in 1970–1972 to determine the effects of additional precipitation on production. Plant material was separated into *Festuca idahoensis, Agropyron spicatum, Bromus tectorum,* miscellaneous forbs, and litter; dried at 60°C; and weighed. Plots were located in a randomized block design i.e., in each treatment area ten blocks were selected for their similarity to each other and to blocks in other treatment areas, and in each of these blocks 30 plots were designated, from which one was randomly chosen at each clipping date. Clipping was similar in 1969 to that of 1970–1972 except that 2 × 5-dm plots were used, the plot frame was "thrown randomly," material from the ten frames clipped was pooled prohibiting the calculation of standard errors, and the 10 and 20% plot treatments were clipped at maximum standing crop rather than fortnightly.

Table 1. Meterological conditions at Bozeman, Mont., and at the study site, 1969–1972.

Month	Normal[1]	1969	1970	1971	1972
		Mean Monthly Temperatures at Bozeman			
April	6	9	2	5	5
May	11	12	11	11	11
June	14	13	16	14	17
July	19	19	20	18	18
August	18	20	21	22	19
		Monthly Precipitation at Bozeman			
April	44	64	39	72	49
May	85	49	87	56	44
June	75	187	37	73	78
July	29	43	80	7	30
August	30	38	25	18	37
Annual[2]	443	635	492	442	419
		Monthly Precipitation at the Study Site			
May[3]	–	11	20	–	–
June	–	355	92	120	47[4]
July	–	21	83	6	29
August	–	29	10	20	24

[1] Normals are averages of the last 30 years of record at Bozeman.
[2] The year is tabulated as September 1–August 31.
[3] May 16–30.
[4] June 15 through June 30.

Effects of Additions to Summer Rainfall

Additions of approximately 25 mm (1 inch) of water every 3 days to the "constantly wet" plot kept soil water stresses there below two bars throughout the top 75 cm of the soil (Fig. 1, June 23, 1971 on). Soil water stress periods in 25 and 75 cm horizons were similar in the plots receiving natural rainfall and natural rainfall supplemented by 40% (80 mm in 1970, 0 mm in 1971, and 41mm in 1972). The 40% supplement to natural rainfall shortened the soil water stress period only in the 10-cm horizon; see 1972 in Figure 1. Supplements of less than 40% did not significantly affect the length of soil water stress periods in any layer. These results might have been expected since most showers falling on dry soils were too small to wet them to 10 cm, and most precipitation entering moist (field capacity) soils percolated downward to depths greater than 75 cm.

Four observations of the effects of supplemental rainfall on plant phenology follow: (1) Species whose growth periods were essentially complete before watering began were apparently unaffected by supplemental water. These early spring species included *Lomatium macrocarpum, Lomatium simplex, Fritillaria pudica, Delphinium bicolor, Mertensia oblongifolia, Phlox hoodii, Crepis acuminata,* and *Bromus tectorum.* (2) The flowering period of *Tragopogon dubius* was clearly extended by constant watering in 1971 and 1972, but was apparently not extended in any other species. Lesser supplements had no effect on any species. The blooming period of *Balsamorhiza sagittata, Festuca idahoensis,* and perhaps *Agropyron spicatum* ended at or before the onset of significant soil water stresses. The cool April of 1970 may have slightly delayed blooming in *Balsamorhiza sagittata* and *Achillea millefolium.* (3) The length of the "live leaf" period was generally increased by constant watering, but was unaffected by lesser additions. In relatively dry 1971, *Balsamorhiza sagittata, Agropyron spicatum, Lupinus sericeus, Achillea millefolium,* and *Tragopogon dubius* browned in early August on all plots

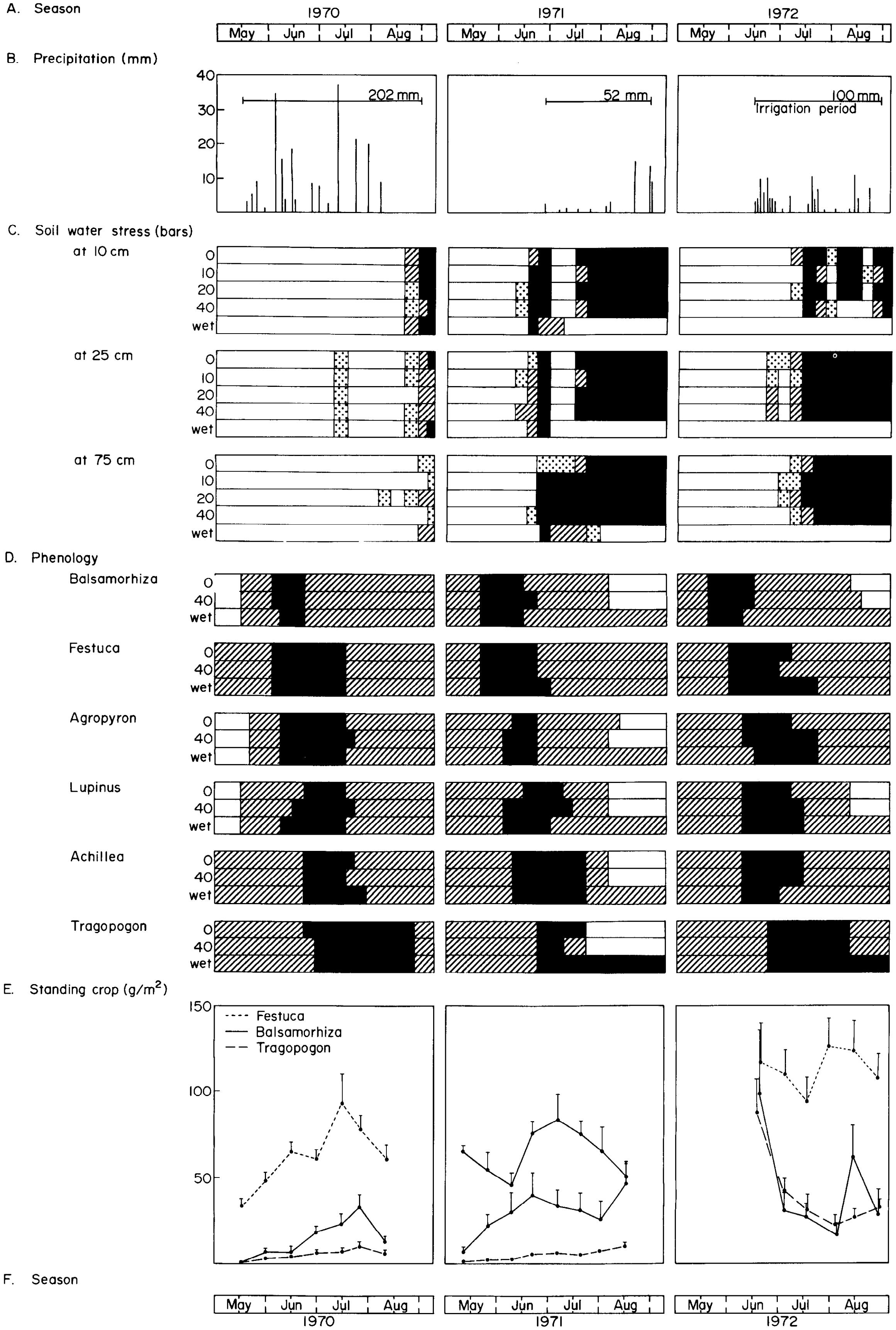

Fig. 1. *The effects of irrigation on soil water, plant phenology, and production of three species in a* Festuca idahoensis-Agropyron spicatum *grassland. (A and F) Time scales for the graphs between. (B) Precipitation deposited by storms in the irrigation period. (C) Soil water stresses on treatments given 0, 10, 20, and 40% supplements to natural rainfall or kept constantly wet (wet). Water stresses are compared at three depths: 10 cm, 25 cm, and 75 cm. Unshaded areas indicate stresses less than 2 bars, stippled areas indicate stresses of 2–5 bars, hatched areas indicate stresses of 5–10 bars, and blackened areas indicate stresses greater than 10 bars. (D) Summer phenologies of* Balsamorhiza sagittata *(BASA),* Festuca idahoensis *(FEID),* Agropyron spicatum *(AGSP),* Lupinus sericeus *(LUSE),* Achillea millefolium *(ACMI), and* Tragopogon dubius *(TRDU) on plots receiving 0 and 40% supplements to natural rainfall or kept constantly wet (wet). The 'constantly wet' plot only received 105% of natural rainfall in 1970. Hatched zones indicate periods when the plants had live leaves and blackened zones indicate flowering periods. (E) The seasonal progression of standing crop for* Festuca idahoensis *(FEID),* Balsamorhiza sagittata *(BASA), and* Tragopogon dubius *(TRDU), three species which respond to added water, in the constantly wet plot, is shown.*

except the constantly wet plot, while *Festuca idahoensis* retained substantial numbers of green leaves despite dry soils. In slightly moister 1972, *Balsamorhiza sagittata* and *Lupinus sericeus* browned in mid-August on all plots except the constantly wet plot while the other plants remained green. In relatively moist 1970, leaves of all these plants remained green through early September. *Balsamorhiza sagittata, Agropyron spicatum,* and *Lupinus sericeus* came into leaf after May 1, 1970, (i.e., late) because the spring was cool: April, 1970, temperatures averaged 3.7°C below normal while they were within 0.5°C of normal in 1971–1972. (4) Though leaves remained green longer when water was added, late season aboveground production was low or nonexistent even in the constantly wet (< 2 bars) plots. This is illustrated by graphs of standing crops of *Festuca idahoensis, Balsamorhiza sagittata,* and *Tragopogon dubius,* the three species responsible for the 1972 production response on the constantly wet plot; they show little growth after July 1 in either 1971 or 1972 (Fig. 1). (The reader will remember that the constantly wet plot received only 105% of natural rainfall in 1969–1970.)

Net primary production was estimated for each plot and each year by maximum standing crop, sum of species peaks, and trough-peak analysis with tests for significant differences at the 95%, 89%, and 0% levels (Kelly et al. 1974; and Singh et al. 1975). The results acquired by summing, for each species or group of species clipped, the largest live weight observed appears in Figure 2. Across all treatments the maximum standing crops observed averaged 83% of the sum of species peaks estimate. Across all treatments the sum of species peaks estimate averaged 95%, 92%, and 84% of trough-peak estimates made with 95%, 80%, and 0% probability that a peak is significantly higher than the preceding trough. Of the total production in all treatments 34% was *Festuca idahoensis,* 9% was *Agropyron spicatum,* 5% was *Bromus tectorum,* 8% was miscellaneous grasses, 21% was *Balsamorhiza sagittata,* 5% was *Tragopogon dubius,* 6% was *Lupinus sericeus,* and 12% was miscellaneous forbs.

Production on plots given 10%, 20%, and 40% rainfall supplements was never significantly greater than on the plot receiving no supplement. The absence of a response to sprinkling in 1970 might be attributed to regular rains through early August and the lack of potentially limiting soil water stresses till late August when plant growth potential had become limiting. No response to sprinkling should be expected in 1971 since the lack of summer storms resulted in no addition of water. The apparent response to the 20% and 40% rainfall supplements in 1972 is not statistically significant even at the 20% confidence level; it is due in the 40% treatment to growth of *Balsamorhiza sagittata* which occurred before sprinkling began; and it is due in the 20% treatment to a "response" of *Festuca idahoensis* which did not occur in the 40% treatment. Two explanations for the failure of supplemental rainfall to increase production seem possible: (1) One might argue, probably incorrectly, that none of the water added reached the plants due to small natural showers which resulted in light supplemental additions, high canopy catch, and high clothesline effect (= small plot size, Tanner 1957). This is doubtful because 7, 7, 0, and 0 rains exceeded 1.25 cm in 1969–1972, respectively; the canopy is a rather open bunchgrass type; the plots are relatively large (0.40 ha); and soil water stresses at 10 cm were reduced, especially in 1972, by sprinkling on the 40% plot (Fig. 1). (2) The argument that water doesn't limit current aboveground growth of plants on this site appears stronger for three reasons. In similar grasslands yields were correlated only with precipitation in May (Mueggler 1972) when soil water stresses on our site were less than 2 bars (Fig. 1). In other grasslands of the northern plains. April through mid-June precipitation controlled yields (see below) and in this period, too, soil water stresses on our site were less than 2 bars. Production on our control sites was very similar from year to year despite the relatively moist springs (April–June) of 1969 (96 mm more precipitation than normal in Bozeman) and 1971 (+ 49 mm) and the relatively dry springs of 1970 (− 16 mm), and 1972 (− 41 mm).

Production of plots kept "constantly wet" was increased significantly (90% level) in 1972, but not in 1971. The yield increase observed in 1972 was due to increased production of *Festuca idahoensis, Balsamorhiza sagittata,* and *Tragopogon dubius.* When one graphs standing crops of these species against time (Fig. 1), he sees that most of the material produced by these species was produced before sprinkling began (June 15, 1972), so the increased production observed must be a product of 1971 watering. The heavy production of these species is not due to use in 1972 of water stored in 2971, however, because soils in the control and lightly sprinkled plots were brought to field capacity by natural rains before the growing season began—they were

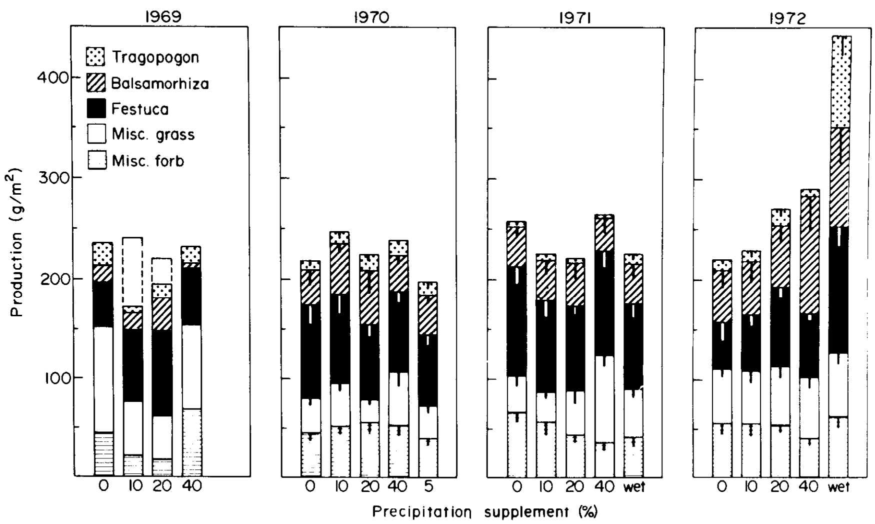

Fig. 2. *Aboveground production on plots receiving 0, 10, 20, or 40% supplements to natural rainfall or kept constantly wet (wet). The constantly wet plot (water stresses below 2 bars) was only given a 5% supplement to natural rainfall in 1969 and 1970. Production was estimated by summing the maximum standing crops of* Tragopogon dubius *(TRDU),* Balsamorhiza sagittata *(BASA),* Festuca idahoensis *(FEID), miscellaneous grasses (MIGR), and miscellaneous forbs (MIFB); standard errors of the maximum standing crops are indicated by bars. Heights of the 1969 10% and 20% estimates are increased (dashed lines) on the assumption that these maximum standing crop estimates are 83% of what a sum of the species peaks estimate would have been (see text).*

rewet to 10 cm by mid-September, to 25 cm by early October, and to 75 cm by early March (Weaver 1975). One may speculate, therefore, that the postponed production is a product of plant reserve materials stored during August of 1971 while plants were "green but not growing" or a product of high decomposition and nutrient release rates during the normally dry late summer.

Other Studies of Precipitation Effects

Regression studies generally demonstrate increased yields on native range with increases in effective precipitation. In the *Bouteloua gracilis-Agropyron smithii-Stipa comata* type of the western Dakotas, Whitman and Haugse (1972) reported yield increases on two native range sites of about 44 kg/ha/cm of precipitation. In *Bouteloua gracilis-Agropyron smithii* types of Alberta, Montana, and Wyoming, yield increases of 34 kg/ha/cm (Smoliak 1956), 32 kg/ha/cm (Ballard 1974), less than 35 kg/ha/cm (Caprio and Williams 1973), and 32 kg/ha/cm (Noller 1968) were reported. In shrub grasslands dominated by *Artemisia tridentata,* responses of 17 kg/ha/cm (Blaisdell 1958) and 15 kg/ha/cm (Noller 1968) were reported. And in *Festuca idahoensis* grasslands above 2,100 m Mueggler (1972) reported responses of 74 kg/ha/cm. Kg/ha/cm may be converted to pounds/acre/inch by multiplying by 2.26. All of these studies emphasize the importance of correlating yield with periods of rainfall that are effective in production; with precipitation, in other words, that falls either in early parts of the growing season (usually April through mid-June) or in water storage periods of the previous fall (Rogler and Haas 1947; Caprio and Williams 1973; Blaisdell 1958; and Noller 1968). Results of Caprio and Williams (1973) suggest that rainfall associated with the previous growing season may also be effective, probably through effects on plant vigor. On consideration of site to site variation Sneva and Hyder (1962) conclude for the intermountain region that a 1% increase (or decrease) in rainfall over the median will result in a 1% increase (or decrease) in yield over the median yield.

In contrast to the cool-season grassland we studied, irrigation experiments show that constant watering may increase the yields of warm season grasslands dominated by *Bouteloua gracilis* significantly (Klages and Ryerson 1965; Smika et al. 1965; and Lauenroth and Sims 1973). Water spreading experiments show that water applied in the rainy seasons and in proportion (unknown) to actual rainfall can increase yields on sites dominated by *Bouteloua gracilis* or *Agropyron Smithii* by 16 to 350% (Branson 1956; Huston 1960; Cosper and Thomas 1961).

Conclusions

The regression studies summarized above indicate that short-term additions to rainfall in the fall and early spring (April through mid-June) may increase yields on relatively good sites in the northern plains at rates of about 31 kg/ha/cm in *Bouteloua gracilis-Agropyron smithii* grasslands to 75 kg/ha/cm in *Festuca idahoensis* grasslands.

Our studies suggest, however, that cloud seeding in the summer months (mid-June through August) may not immediately increase yields of grasslands in the northern plains. On our irrigated *Festuca Idahoensis-Agropyron spicatum* plots, for example, we observed no increased production when natural rainfall was supplemented by 40% i.e., when May through mid-June precipitation was increased by 5.3, 3.3, 0.0, and 0.0 cm in 1969–1972 and when mid-June through August precipitation was increased by 8.1, 4.6, 0.0, and 4.1 cm in 1969–1972, respectively. A spring response was probably lacking because water was not a limiting factor on the study site through mid-June. A summer response was probably lacking because additions as large as 0.4 times natural rainfall were far too small to be effective during the summer period. Regular large additions to soil water (5 cm irrigation weekly) increased harvestable yields in the year following that in which they were made, probably by increasing plant reserves and vigor.

Would a really larger *Bouteloua gracilis-Agropyron smithii* grasslands respond to increased summer rainfall as the *Festuca idahoensis-Agropyron spicatum* grassland did? Increased yield might be observed after several years if increased summer precipitation resulted either in increased vigor and/or densities of existing grasses or replacement of these with more productive grasses. On the other hand decreased yields might be observed if increased summer precipitation resulted in increased importance of less productive grasses such as *Bouteloua gracilis* (Lewis 1970).

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