agronomy

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Impacts of Irrigation Technology, Irrigation Rate, and Drought-Tolerant Genetics on Silage Corn Production

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Abstract: Many studies have examined individual water-saving management practices for corn (*Zea mays* L.), but few studies have looked at how combinations of practices might further enhance water optimization. The research objectives of this paper were to evaluate the impact of irrigation technology, irrigation rate, and crop genetics, as well as their interactions, on silage corn yield and forage quality. Trials were conducted in three Utah locations from 2019 through 2021. The results from five site-years indicated that the best water optimization practices varied by site-year. Low-elevation sprinklers commonly applied water more efficiently, with four of the five site-years having improved or equivalent yield compared to mid-elevation sprinklers. Irrigation rate reductions and yield losses were not proportional, as a 25% irrigation reduction resulted in better silage quality and a 7% average yield loss across site-years. Further, targeted deficit irrigation (less water during vegetation and more during maturation) was inferior to a uniform deficit during all growth stages. Drought-tolerant genetics often maintained but did not improve yield in extreme water stress environments compared to non-DT genetics. No cumulative benefits were observed when combining irrigation technology, rate, and DT genetics. Irrigation technology had the greatest potential of the three factors to optimize water use in silage corn production in the Western U.S. region.

Keywords: silage corn; water resource management; irrigation methods and tools; drought-tolerant crop genetics; plant–water relations

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Citation: Sullivan, T.; Yost, M.A.; Boren, D.; Creech, E.; Kitchen, B.; Violett, R.; Barker, B. Impacts of Irrigation Technology, Irrigation Rate, and Drought-Tolerant Genetics on Silage Corn Production. *Agronomy* **2023**, *13*, 1194. https://doi.org/10.3390/agronomy13051194

Academic Editors: Shicheng Yan, Yongzong Lu, Shengcai Qiang and Tiebiao Zhao

Received: 31 March 2023
Revised: 19 April 2023
Accepted: 22 April 2023
Published: 24 April 2023

1. Introduction

Agriculture is the largest consumer of diverted water in most of the Western U.S. [1]. Increases in urban growth, less projected winter snowpack, watershed depletions, and persistence in drought continue to point toward the need to optimize and conserve water used for agriculture [2–4]. Agricultural producers have several potential options to optimize water use. Crop hybrids or cultivars with drought tolerance, reduced tillage to enhance soil moisture, cover crops to reduce runoff velocity from rainfall or snowmelt, alternative irrigation sprinkler technologies, alternate crops, fallowing, and deficit irrigation strategies are a few techniques [5–7]. With several options available and significant investments needed for some practices, growers, water managers, and policymakers often struggle to prioritize which practices should be promoted and adopted. Though implementing them all into a single production setting is impractical, knowing which combinations offer the greatest reduction in water use could lead to greater acceptance and use of these practices.

Growers may optimize water use by refining irrigation systems and management with the use of center-pivot or lateral-move systems and more modern sprinkler options. Advanced systems have been developed to reduce evaporation, wind drift, and runoff.

Some of the most notable alternative systems to the conventional mid-elevation spray application (MESA) sprinklers include low-energy precision application (LEPA), low-elevation sprinkler application (LESA), and mobile drip irrigation (MDI). Numerous studies show these technologies' water-saving abilities compared to on top or MESA systems, and they are more cost effective compared to subsurface drip [8–10]. For LESA, a study in the Pacific Northwest with grower cooperation found that using LESA sprinklers led to better corn (*Zea mays* L.) stand uniformity than MESA [11]. In a similar area, a three-year study found on average 21% more of the irrigation water from a LESA system reached the ground compared to MESA [12]. Furthermore, most comparisons of LEPA, LESA, and MDI to MESA are conducted at full irrigation rates, which does not allow for the testing of enhanced production efficiency with less applied irrigation. Thus, the ability of advanced irrigation systems to maintain production with reduced irrigation needs to be documented.

Deficit irrigation can be defined as any irrigation strategy that does not meet the full evapotranspiration (ET) demand of a crop. Many studies have investigated the use of deficit irrigation and found that it can substantially minimize yield loss and increase water use efficiency if applied correctly at critical crop growth stages [5,13,14]. Many of these studies were conducted in the Midwest or South, where irrigation is often not as critical for corn production as the Intermountain West. Irrigation might also be a strategic choice in some cases for income through water markets, where conservation payments or program incentives support cutting back on the practice. Whether intentional or not, deficit irrigation will often cause yield, quality, and profit loss. In many cases, deficit irrigation strategies with varying effectiveness can be employed to maximize production and profit. These strategies can include modifying irrigation schedules, concentrating irrigation to critical crop growth stages, reducing rates, terminating irrigation early, or increasing irrigation efficiency in various ways, with some providing economic benefits [15]. These previous studies suggest the functionality of using deficit irrigation strategies but rarely compare how uniform deficit irrigation compares to targeted deficit irrigation strategies for corn silage, specifically in arid areas.

Achieving water conservation with drought-tolerant crops can be accomplished with varieties that utilize water more efficiently to produce biomass and grain. Both breeding and genetic modifications that have enhanced corn drought tolerance and became commercially available in 2011 for commercial and in 2012 for genetically engineered crops focused in the U.S. Corn Belt region [16]. Conventional breeding efforts for drought-tolerant hybrids have drought-minimizing yield mechanisms such as leaf area reduction, lighter dry weights of shoots, more developed root systems, and ear size based on water availability [17]. Drought-tolerant (DT) varieties were developed by DuPont Pioneer (Pioneer Hi-Bred International, Johnston, IA, USA) as AquaMax® and premerger Monsanto (Bayer Crop Sciences, Leverkusen, Germany) as DroughtGard®. Trials involving hybrids with these traits in water-limited environments have documented higher yields with DT corn hybrids compared to conventional varieties [18–20]. When DuPont Pioneer released their conventional breeding option, these varieties exhibited higher grain yield than regular hybrids in both drought and non-drought environments [21]. The Monsanto DT hybrids were developed using gene suppression, allowing corn to have a yield advantage in water-stressed environments. The early United States and Chile pre-release tests showed the hybrid was able to maintain the same quality parameters as the conventional hybrids in different limited irrigation environments [22]. Results from these various studies found no statistical difference in yield under irrigated situations and significantly higher yield in dryland situations.

Limited studies have been conducted to compare DT corn varieties to their non-DT counterparts in arid U.S. West regions under irrigation treatments with silage as the end use. Most DT hybrid trials have been conducted in the U.S. Corn Belt or High Plains. In these regions, mixed grain yield responses occurred with variability in drought-tolerant genetics, handling drought stress better than their conventional counterparts and not being able to determine water conservation [23–25]. Knowing drought-tolerant corn hybrids may better handle the limited irrigation environment in the Texas High Plains or the Corn Belt is essential but not transferrable to the soil types, elevation, and climate of the Intermountain West.

The Intermountain West has had limited testing of irrigation systems, deficit irrigation, and DT genetics in silage corn production. Further, no studies in this region or elsewhere have combined these factors to determine how combining them might provide cumulative or additive water conservation benefits. Thus, the objectives of this research were to evaluate the impact of irrigation technology, irrigation rate, and crop genetics, as well as their interactions, on silage corn yield and forage quality.

2. Materials and Methods

2.1. Site Characteristics

Trials were conducted in Logan, Utah in 2019 and 2020, Vernal, Utah in 2020 and 2021, and Cedar City, Utah in 2021. Soil classifications were obtained from the University of California-Davis SoilWeb [26] (Table 1), and soil texture, pH, and salinity were measured at the Utah State University Analytical Lab (Logan, UT, USA) using standardized protocols. pH values were found with a saturated paste extract protocol in which the soil is brought to saturation with deionized water and a pH probe placed directly into the sample. Soil samples were taken at a depth of 0.3 m for tests. The Logan and Cedar City sites have sandy loam soils, and the Vernal site has clay loam soil. Soil organic matter varied among sites, and Vernal had the greatest levels and Cedar City the lowest (Table 1).

Table 1. Site and soil properties for five trials in Utah from 2019 to 2021.

Nearest Town	Years	GPS Coordinates	Elevation	Dominant Soil Texture (Classification)	Soil Organic Matter (%)	Soil pH	Salinity (dS m^{-1})
Logan	2019–2020	41.6617, −111.9229	1365	Sandy loam (fine-silty, mixed, mesic Aquic Calciustolls)	2.7	7.4	0.57
Vernal	2020–2021	40.4620, −109.5608	1667	Clay loam, loam (fine-loamy, mixed, superactive, calcareous, mesic Typic Torriorthents)	3.1	7.6	0.58
Cedar City	2021	40.4620, −109.5608	1682	Sandy loam, silty clay loam (coarse-loamy, mixed (calcareous), mesic Xeric Torriorthents)	1.8	7.6	1.6

Daily weather data at the three sites were obtained from the Utah Climate Center (Logan, UT, USA) and were used to calculate cumulative precipitation and growing degree days for each season. The corn growing degree days (GDDs) were calculated using a base air temperature of 10 °C and an upper threshold of 30 °C. These values are the standard base temperature and upper limits for corn despite end use and were thus used for the calculations. Measured cumulative precipitation and degree days were compared with their respective 30-year normal (1991–2020) provided by the National Oceanic and Atmospheric Administration (Silver Springs, MD, USA).

2.2. Treatments

The experimental design was a nested factorial with random factors. Irrigation rate was nested within irrigation technology, as there was limited area in a four-to-five-span lateral-move irrigation system, and randomization of various technologies was not possible due to sprinkler spray patterns. The irrigation technologies were each randomly assigned to one span (48–55 m) of the lateral at each site. This design was selected because randomization of sprinkler technologies was not feasible due to conflicting wetting diameters and available space on the lateral-move irrigation system. The irrigation system treatments were similar but not identical at the three locations. Logan and Vernal had MESA, LESA, MDI, and LEPA. Cedar City had MESA, LESA, and LEPA but had LENA (low-elevation Nelson Advantage®, Nelson Irrigation, Walla Walla, WA, USA) instead of MDI. The LENA system was also tested at the Logan site in addition to the other four systems because it was a five-span lateral, and space existed. Each site's lateral-move machine had set operating m^3 h^{-1} and pressures. Th system flows were 91.1, 99.9, and 145.4 m^3 h^{-1}, respectively, for the Logan, Vernal, and Cedar City sites. The operating pressure for Logan and Vernal was 30 PSI, and Cedar City's was 40 PSI.

The irrigation rates at all sites were targeted for seasonal uniform applications of full-of-deficit irrigation levels as a fraction of ET that included 100%, 75%, 50%, and 50% prioritized application based on the crop growth stage. The prioritized or targeted rate's goal was to use 50% of the growing season's ET allotment with varying rates over the season. Germination, tasseling, and silking stages were noted as priority stages, whereas late vegetation and seed fill were not for irrigation. The treatments were randomly assigned to a quarter of each span. Irrigation rate treatments were accomplished by adjusting nozzle sizes in each treatment. To reduce the overlap in rates between treatments, a pair of directional sprinklers (semi-circular application patterns) were installed between plots in MESA but not the other systems, because they had much smaller throw patterns and much less overlap. At the beginning of each season at each site, a uniform depth of irrigation was applied to the entire study area before planting (if necessary) and for the first irrigation directly after planting to ensure uniform corn germination and emergence. Two irrigations with extremely dry springs were uniformly applied after planting for the seasons before rate treatments were implemented. The MESA system was the conventional treatment or grower standard due to its widespread use.

The 100% or full irrigation rate was set in a variety of ways. To the extent possible, full irrigation rates were based on ET estimates from the Irrigation Scheduler program [27]. This Irrigation Scheduler program used crop coefficient values based on the crop selected and implements Kc values according to maturation stages. There is not a different Kc recognized for silage corn than for grain corn. We also utilized the irrigation experience of farm managers at each site. Some sites had limited ability to adjust irrigation timing, so only applied depth could be adjusted to achieve the full irrigation treatment. This was most apparent in Logan, where the surface water supply was on a preset turn-based schedule approximately every two weeks. The Vernal site was also irrigated with surface water but was on an order-based system, which allowed for more flexibility in irrigation timing and rate. In 2021 at Vernal, irrigation ceased in July due to a water shortage caused by a widespread and historic drought. The Cedar City site had the greatest irrigation flexibility, as it was not limited by turns but by volume pumped.

The 50% targeted irrigation treatment was designed to receive 50% of the total irrigation rate applied across the season, but with targeting of water to critical crop growth stages rather than a uniform 50% rate reduction every irrigation. To accomplish this, nozzles were switched back and forth from 100, 50, or 0% rates to create an average of 50%. Irrigation was reduced or eliminated during the early vegetative stages, increased during tasseling and silking, then reduced after silking. The targeted 50% reduction was not always a 50% reduction, but rather ranged from 50–87% due to water turn and water availability uncertainties in some site years.

Two crop genetic treatments (DT vs. non-DT corn hybrids) were implemented and replicated three times randomly within each irrigation system and rate treatment. Corn genetic plots were 9.5 m long by 6.1 m wide (eight 76.2 cm-wide corn rows). Corn was planted with commercial planters at each site at a seeding rate of 88,980 plants ha^{-1} at 5.1 cm deep in mid-May of each site-year. The two seed types planted in 2019 in Logan were DKC 51–20 as the DT hybrid and DKC 50–84 as the non-DT hybrid. The hybrid pair was changed to DKC 47–27 as the DT hybrid and DKC 46–36 as the non-DT hybrid in 2020 and 2021 at all three sites for the corresponding growing seasons, because the former hybrids were no longer commercially available. The traits, relative maturity, and other characteristics of the two hybrid pairs each year were as similar as possible, except for the DT variety having the DroughtGard® trait. All varieties had SmartStax® technology with relative maturities of 95 and 96 days to ensure harvestability at all three sites with different frost period lengths.

Tillage types varied slightly among sites according to local soil and site conditions. Tillage typically included disking once or twice in the fall and then field cultivating once or twice in the spring to prepare the seed bed. Chisel plows and rippers were used periodically in the fall in Cedar City to alleviate compaction. Planting populations, fertilization, and pest management operations were conducted uniformly across the entire plot area. Fertilizer rates for the sites were based on soil tests conducted in the spring of each season and Utah State University Extension Guidelines [28]. In 2019 for Logan, 2020 for Vernal, and 2021 Cedar City, N fertilizer was not applied, because it was first-year corn following alfalfa, and no N response was expected [29]. In subsequent site-years, soil samples were taken at a depth of 0.3 m to determine soil nitrate levels compared to university guidelines, and they were fertilized accordingly to ensure fertilizer was not a limiting factor in this study.

2.3. Crop Yield and Quality

Corn was harvested at the dent stage (R5) in late September of each site-year using a GEHL pull-type two-row harvester (GEHL, Marllete, MI, USA). Corn was cut roughly 15 cm above the ground and the length (8 m) of the center two rows of each plot. Corn was blown from the harvester into a pull-type weigh wagon to collect bulk weights. A subsample (~0.45 kg) was pulled from bulk samples, weighed, and dried at 60 °C until constant mass and processed. In 2021, the Cedar City site was hand-harvested due to limited equipment availability. For each plot, plants were cut 15 cm above the soil surface in 3 m of the center two rows of each plot. All cut plants were weighed in the field, and a subsample of four plants from each plot were chipped in an Echo Beat Cat SC3206 Chipper Shredder (Crary Industries, West Fargo, ND, USA). Subsamples of chipped corn (~0.50 kg) were weighed and then dried in a forced-air oven at 60 °C until constant mass. Dried samples from all sites were weighed, ground to pass through a 1 mm screen using a Thomas Wiley Laboratory Mill Model 4 (Thomas Scientific, Swedesboro, NJ, USA) and analyzed for forage quality.

Forage quality analysis occurred at the Utah State Analytical Laboratories (Logan, UT, USA) with near-infrared reflectance spectroscopy (NIRS) using a FOSS DS2500F (Foss North American Inc., Eden Prairie, MN, USA). The 2019, 2020, and 2021 unfermented corn NIRS consortium equations (NIRS Forage and Feed Consortium, Berea, KY, USA) were used to estimate dry matter, ash, fat, crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), starch, total digestible nutrients (TDN), and 48 h digestible NDF (NDFD48). All values reported are in percentages. TDN was calculated using the following equation.

$$TDN = 0.98[100 - (NDF - 2 + CP + 2.5 + Ash)] + 0.93CP + 0.97(2.25)(Fat - 1) + \frac{NDFD(NDF - 2)}{100} - 7$$

2.4. Statistical Analysis

All statistical analyses were performed by site at $p \leq 0.05$ using the MIXED procedure of SAS (SAS Version 9.4, SAS Institute Incorporated, Cary, NC, USA). Each site was analyzed separately, because the treatments varied slightly among sites. In all analyses, main effects and most interactions of irrigation technology, irrigation rate, and crop genetics were considered fixed factors. The exception was the interaction of irrigation technology and irrigation, which was treated as a random factor with the block nested within the interaction. Residuals were evaluated for homogeneity of variance and normality using scatterplots of residuals versus predicted values with the UNIVARIATE procedure of SAS. All mean separations were conducted using Fisher's protected LSD at α = 0.05 using the PDIFF option of the MIXED procedure.

3. Results

3.1. Weather, Soil Productivity, and Irrigation

The total growing season (1 May to 30 September) precipitation for Logan was 196 mm in 2019 and 104 mm in 2020. These values were 28% more and 26% less than the 30-year normal of 141 mm in 2019 and 2020, respectively (Figure 1). Cumulative growing degree days (GDD) in Logan was 2213 degree days for 2019 and 2427 for 2020, which was below the 30-year normal of 2375 for 2019 and above it for 2020. Vernal had a total growing season precipitation of 47 mm in 2020 and 120 mm in 2021. The 2020 precipitation was much lower than the 30-year average of 107 mm and, despite a major drought in 2021, there was above average precipitation due to late-season monsoonal rain (Figure 1). Compared to the 30-year average GDD of 2481 growing degree days for Vernal, 2020 was 2653 and 2021 was 2770. These years were 6% and 10% higher than the 30-year normal, respectively. Cedar City had a total growing seasonal precipitation of 161 mm in 2021, which was 22% higher than the 30-year normal of 126 mm. The extreme monsoonal rains (107 mm) provided 84% of the normal growing season (1 May to 30 September) moisture in a 21-day period, which increased the overall precipitation amount for the season (Figure 2). The 2021 season at Cedar City was also cooler than normal, with 144 degree days less than the 30-year normal of 2737 degree days.

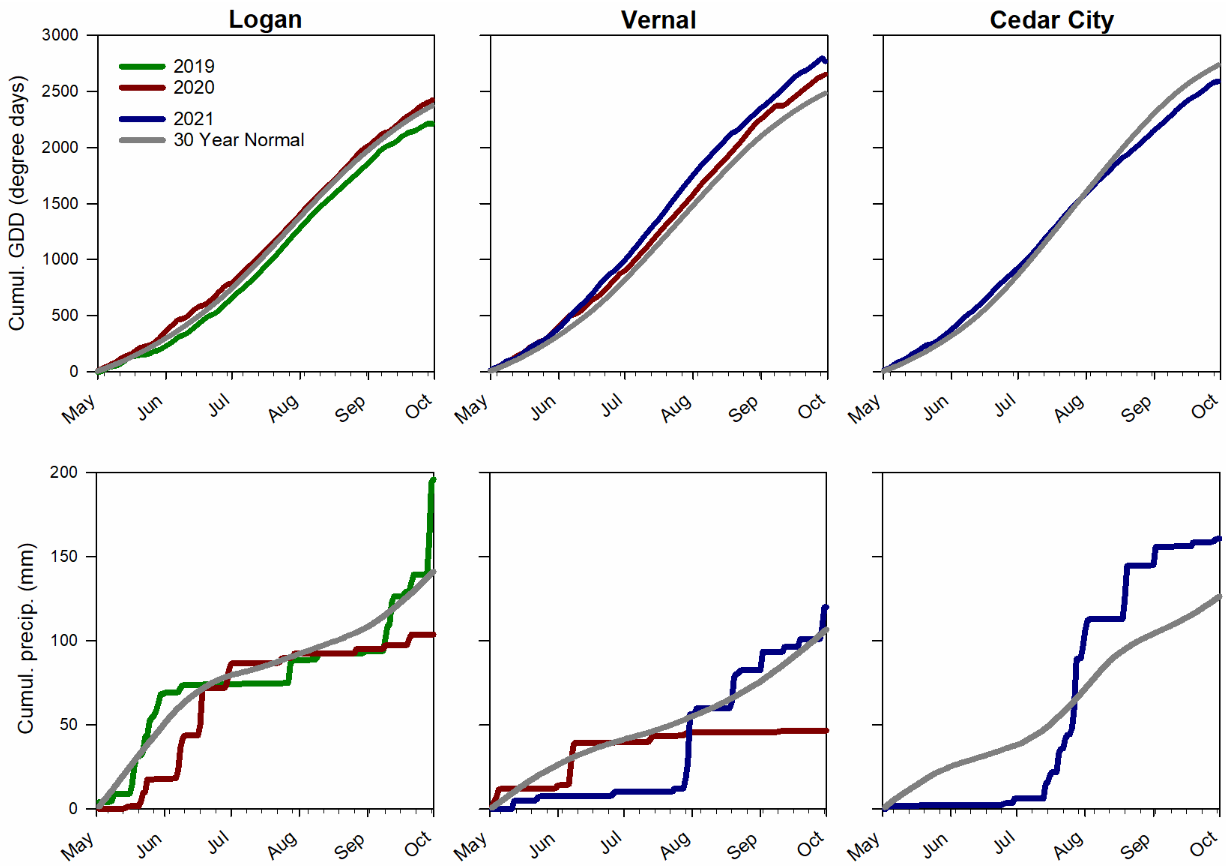

Figure 1. Weather conditions during the corn growing season (1 May–30 September) for five site-years in Utah, including daily cumulative precipitation (mm) and daily cumulative growing degree days (GDD) with a base of 10 °C and upper threshold of 30 °C, compared to the 30-year climate normal (1991–2020).

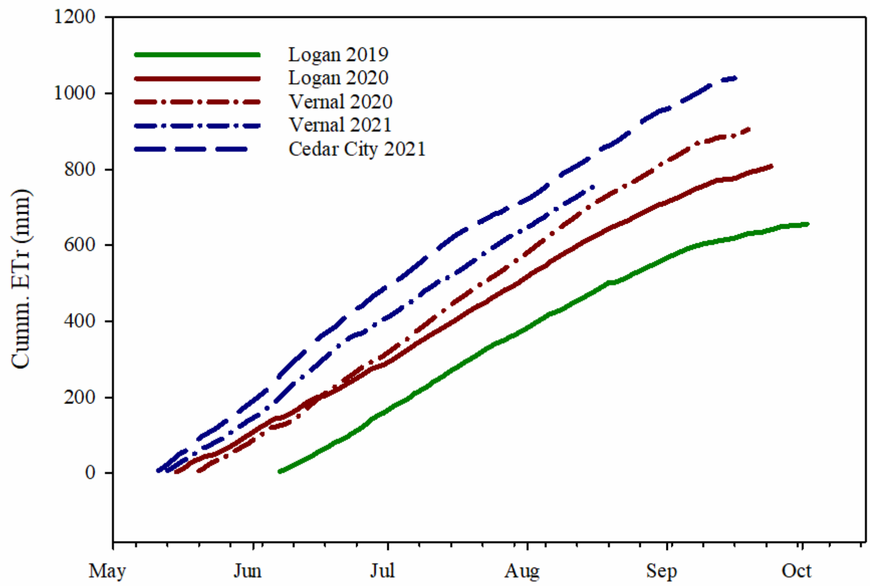

Figure 2. Cumulative tall reference evapotranspiration (ETr) calculated from the local weather station data for each site-year.

Different soil types and weather often lead to different irrigation needs, which is evident from irrigation totals (Table 2), reference ET (Figure 3), and yields for the 100% irrigation rate for each site. For 2019, the above-average precipitation year, 330 mm of irrigation was used for the full irrigation rate and yielded 19.5 Mg ha^{-1} across all treatments excluding rate. The drier year of 2020 at both Logan and Vernal displayed similar yields to one another, but required different irrigation amounts to reach those levels. Logan was irrigated with 350 mm and produced 26.6 Mg ha^{-1} of silage corn, and Vernal with 70 cm of irrigation to produce 26.3 Mg ha^{-1}. These yields, irrigation amounts, and reference ET (Figure 2; Table 2) demonstrate that the soils in Vernal demand a higher quantity of irrigation compared to Logan. The difference in yield between 2019 and 2020 for Logan with roughly the same irrigation amounts is also noteworthy, though yield was limited for 2019 by the shorter growing season, with the corn planted June 7th due to wet conditions in May. The Cedar City and Vernal sites were planted one day apart in 2021. Cedar City had a full irrigation supply, yielding 19.1 Mg ha^{-1} with 53 cm of irrigation. Vernal did not have a full irrigation supply due to drought, and the highest irrigation level yielded 15.1 Mg ha^{-1} with 290 mm of irrigation.

Table 2. The amount of irrigation applied per site-year for each treatment.

Irrigation Rate	Logan 2019	Logan 2020	Vernal 2020	Vernal 2021	Cedar City 2021
			Total applied irrigation (mm)		
100	330	351	690	286	535
75	248	263	517	215	401
50	165	175	345	143	267
T [a]	235	198	385	208	326

[a] T, targeted deficit irrigation. All other deficit irrigation treatments included uniform reductions all season. The targeted reductions were as follows: 75%, 50%,50%, 87%, and 61%, respectively.

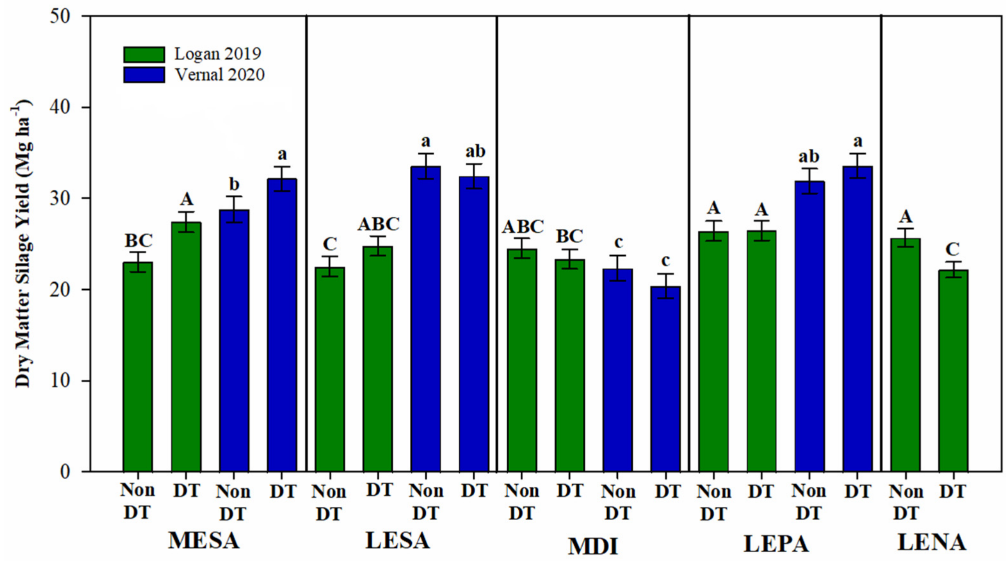

Figure 3. Silage corn yield for interactions of non-drought-tolerant corn genetics (non-DT) and drought-tolerant corn genetics (DT) in five irrigation systems (MESA (mid-elevation spray application), LESA (low-elevation spray application), MDI (mobile drip irrigation), LEPA (low-elevation precision application), and LENA (low-elevation nelson advantage)). Error bars represent standard errors. Letters above bars represent mean separations conducted by site-year with protected Fisher's LSD at α = 0.05. Letter format designates mean separation for each site-year, with uppercase as one and lower case as the other.

Experiments were conducted at these three sites to capture differences across the state in water use and soil quality. The Logan site had medium-textured sandy loam soil with high organic matter and low salinity that created a high productivity environment. Cedar City had a medium-textured soil with a mixture of sandy loam and silty clay loam, but the combination of lower organic matter and higher salinity amounts led to a medium productivity environment. The clay loam soil at Vernal was a heavy, fine soil with medium salinity and high organic matter, but clay soils tend to retain more nutrients and not allow them to be accessed by the crop. Because of the varying soil types and growing conditions and the slight variation in experiment design at each site, the separation of sites for the overall analysis and discussion was chosen (Table 3).

Table 3. Significance of *F* tests for the fixed effects of irrigation technology, irrigation rate, genetics, and their interactions on silage corn yield and quality parameters (CP, crude protein; ADF, acid detergent fiber; NDF, neutral detergent fiber; starch; TDN, total digestible fiber; NDFD48, NDF digestibility in 48 h digestion). Differences were considered statistically significant when $p \leq 0.05$.

Site-Year	Effects	Yield	CP [1]	ADF [1]	NDF [1]	Starch [1]	TDN [1]	NDFD48 [1]
					$p > F$			
Logan 2019	T [2]	0.125	0.144	0.125	0.002	0.327	0.009	0.078
	R [3]	<0.001	0.050	<0.001	<0.001	0.133	0.203	0.026
	G [4]	0.482	0.073	0.482	0.375	0.086	0.749	0.150
	T × G	<0.001	0.312	<0.001	0.134	0.172	0.051	0.364
	R × G	0.196	0.371	0.196	0.186	0.271	0.625	0.254
Logan 2020	T	0.002	0.051	0.002	0.026	0.075	0.005	0.036
	R	0.003	0.493	0.003	0.001	0.951	0.986	0.951
	G	0.460	0.043	0.460	0.005	0.095	<0.001	0.113
	T × G	0.202	0.757	0.202	0.255	0.310	0.03	0.086
	R × G	0.010	0.149	0.010	0.023	0.046	0.752	0.076

Table 3. *Cont.*

Site-Year	Effects	Yield	CP [1]	ADF [1]	NDF [1]	Starch [1]	TDN [1]	NDFD48 [1]
Vernal 2020	T	<0.001	0.223	<0.001	0.004	0.308	0.001	0.430
	R	<0.001	0.087	<0.001	0.063	0.501	0.245	0.210
	G	0.485	0.004	0.485	0.006	0.002	<0.001	0.921
	T × G	0.040	0.655	0.040	0.141	0.842	0.763	0.286
	R × G	0.04	0.004	0.043	0.013	0.039	0.565	0.337
Vernal 2021	T	<0.001	0.819	<0.001	0.001	0.020	<0.001	0.819
	R	<0.001	0.004	<0.001	0.018	0.027	<0.001	0.004
	G	0.077	<0.001	0.077	0.012	0.036	<0.001	<0.001
	T × G	0.463	0.205	0.463	0.371	0.982	0.665	0.205
	R × G	0.094	0.378	0.094	0.810	0.969	0.843	0.379
Cedar City 2021	T	<0.001	<0.001	<0.001	0.444	<0.001	<0.001	<0.001
	R	0.010	0.004	0.010	0.761	0.008	0.050	0.004
	G	0.880	0.207	0.880	0.001	0.157	0.203	0.205
	T × G	0.591	0.662	0.591	0.602	0.499	0.551	0.663
	R × G	0.691	0.423	0.691	0.088	0.565	0.434	0.424

[1] Tested feed quality parameter, [2] irrigation technology, [3] irrigation rate, [4] crop genetics.

3.2. Silage Corn Yield

3.2.1. Irrigation Technology × Genetics Interaction

Two of the five site-years had a significant interaction between irrigation technology and corn genetics for dry matter yield (Table 3). For the 2019 growing season in Logan, DT corn genetics affected silage corn yield in two irrigation systems (MESA and LENA). In MESA, the DT corn hybrid yielded 27.4 Mg ha^{-1} and improved silage yield by 16% compared to the non-DT hybrid (Figure 2). In LENA, the DT hybrid decreased yield by 13% or 3.5 Mg ha^{-1} compared to the non-DT hybrid. Yield was equivalent between corn genetics for the remaining three irrigation systems (LEPA, LESA, and MDI). The yield of the non-DT hybrid was greater in MDI, LEPA, and LENA compared to MESA and LESA. This yield reduction may have been related to less overall plant-available water caused by lower uniformities from lower application efficiencies in MESA and LESA [8] due to wider spacing and higher elevation of sprinklers. The second site-year with a significant interaction between irrigation technology and crop genetics (Table 3) was Vernal in 2020. Results for this site-year were largely consistent with those for Logan in 2019. The DT hybrid only affected yield in MESA, with the DT hybrid yielding 11% more than the non-DT counterpart (Figure 2). Yield of the non-DT hybrid in MESA was lower than LESA, equivalent to LEPA, and greater than MDI. This suggests water stress in MESA may not be the major causal factor in why the DT hybrid yielded a better outcome in MESA. Rather, it may relate more to differences in water distribution patterns in MESA compared to other systems with more uniform water distributions from tighter spacing and lower elevation sprinklers or drip, as distributing water uniformly through a corn canopy has often been a challenge.

Collective results from all five trials indicate that DT corn rarely improved silage corn yield, especially when irrigation uniformity improved with systems other than MESA. The infrequent (two of five site-years) and inconsistent (one of two years at two sites) benefit of the DT hybrid in MESA suggests that DT hybrids may only be beneficial in some cases. At \$65.57 Mg^{-1} for a market price of silage corn and \$3.44 ha^{-1} (price paid in 2020) for the additional cost of the DT hybrid seed compared to the non-DT hybrid, the 11% and 16% increases in corn yield would have paid for the additional seed cost. Thus, DT corn could be an economic option for some producers using MESA systems. However, more data are needed to identify environmental conditions (site, soils, climate) that cause economic advantages to utilizing DT genetics.

3.2.2. Irrigation Rate × Genetics Interaction

Two of the five site-years had significant irrigation rate × corn genetics interactions for dry matter yield (Table 3). Both occurred in 2020 at the Logan and Vernal sites. In Logan, DT genetics increased yield by 10% over the non-DT genetics (41.2 compared to 37.5 Mg ha^{-1}) at the 100% irrigation rate (Figure 4). However, DT genetics did not improve silage corn yield in the three reduced irrigation treatments in which the benefits of DT genetics should be more pronounced. This suggested few to no benefits of the DT genetics in water-stress or drought conditions. However, regardless of corn genetics, the reduced irrigation rates rarely reduced silage corn yield. Despite our best effort to stress corn that year (about 180 mm of irrigation in the 50% irrigation rates compared to 350 in the full irrigation), the low irrigation rates still provided sufficient water to match full irrigation quantity. Thus, drought conditions were not prevalent in that site-year and likely contributed to the lack of response to DT genetics.

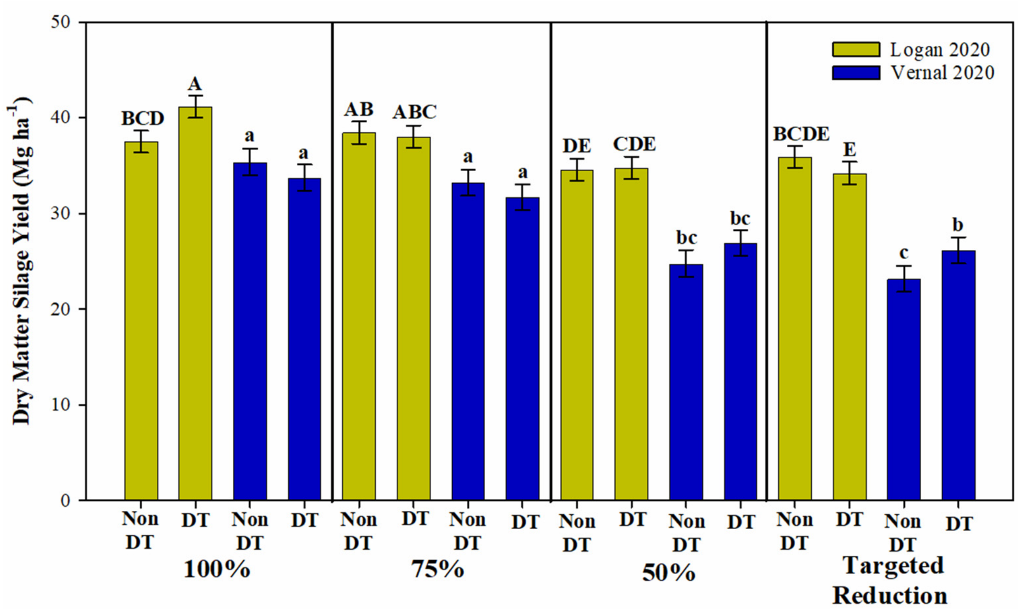

Figure 4. Silage corn yield for interactions of non-drought-tolerant corn genetics (non-DT) and drought-tolerant corn genetics (DT) at four irrigation rates (100%, 75%, 50%, and 50% of estimated evapotranspiration). One 50% rate was a uniform reduction in every irrigation, and the targeted 50% was adjusted to apply more irrigation at critical crop stages and no or less irrigation at other times. Error bars represent standard errors. Letters above bars represent mean separations conducted by site-year with protected Fisher's LSD at $\alpha = 0.05$. Letter format designates mean separation for each site-year, with uppercase as one and lower case as the other.

In contrast to Logan, water stress was apparent in Vernal in 2020, as yield across genetics decreased from an average of 33.5 Mg ha^{-1} in the 100% and 75% rates to 25.3 Mg ha^{-1} in the two 50% irrigation rates. Despite water stress, the DT corn genetics only improved silage corn yield by 13% (from 23.2 to 26.2 Mg DM ha^{-1}) in the 50% targeted irrigation rate (Figure 3). Results do not indicate why the DT genetics improved yield under the targeted irrigation reduction and not the uniform reduction despite both yielding similarly. First, it was indicated that there was no benefit in this site-year to a targeted deficit irrigation. Second, the benefit of the DT genetics in the targeted rate may be related to the timing of water stress. The uniform deficit was water stressed nearly all season, whereas the targeted had intermittent periods of full irrigation, which may have allowed the DT genetics to better handle water stress. This benefit of DT genetics was not consistent, though, as DT had no impact on silage yield at three other site-years with water stress.

3.2.3. Irrigation Technology

The main effect of irrigation technology was highly significant for all site-years except Logan in 2019, where high spring precipitation may have diluted the effects. At Logan in 2020, LESA and LEPA produced equivalent silage corn yield as the grower standard of MESA, but yield decreased by 9 and 18% with LENA and MDI, respectively, compared to MESA (Figure 5). The main effect of irrigation technology at Vernal 2020 could not be assessed because of the significance of the interaction of irrigation technology and crop genetics. It is still instructive to note that for that site-year, LEPA and LESA were statistically similar to MESA, but MDI produced 50% less silage corn yield than the average of those three systems (21.3 compared to 32 Mg ha^{-1}). Vernal in 2021 had a similar trend as 2020, with LESA being slightly higher but statistically equivalent to MESA, and MDI performing the worst. LEPA yielded 38% less than MESA, and MDI yielded 55% less than MESA. In Cedar City in 2021, MESA yielded 15.2 Mg ha^{-1}, which was 59% lower than the average (24.2 Mg ha^{-1}) of the three alternative technologies that were all equivalent.

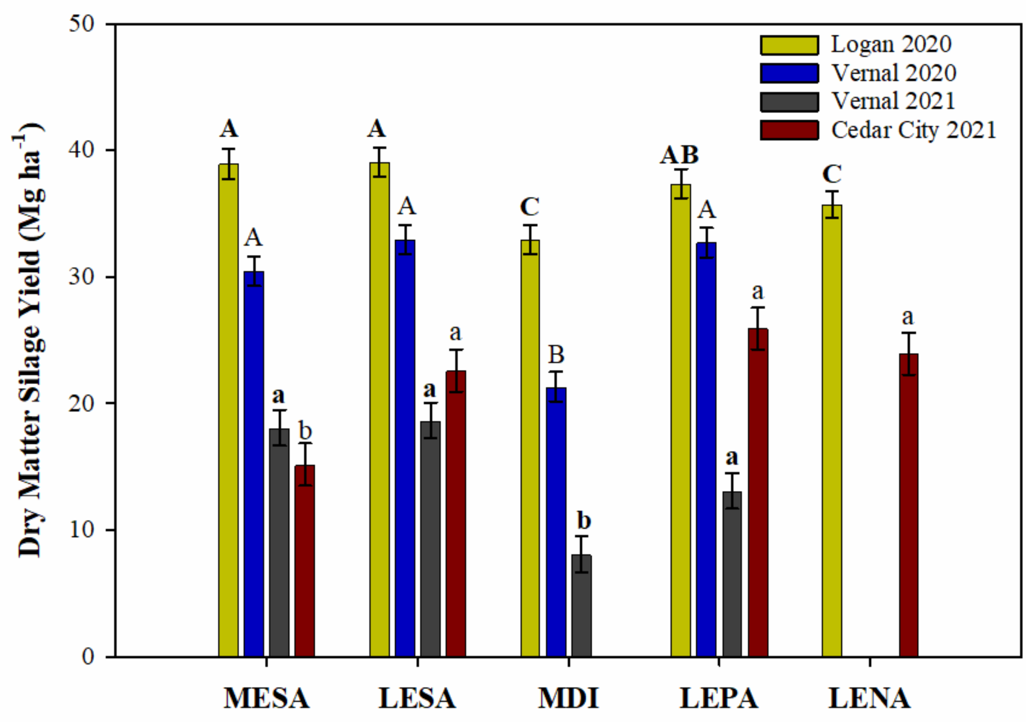

Figure 5. Silage corn yield as impacted by five irrigation systems (MESA (mid-elevation spray application), LESA (low-elevation spray application), MDI (mobile drip irrigation), LEPA (low-elevation precision application), and LENA (low-elevation Nelson Advantage®)). Error bars represent standard errors. Letters above bars represent mean separations conducted by site-year with protected Fisher's LSD at α = 0.05. Letter format designates mean separation for each site-year, with uppercase as one and lower case as the other.

3.2.4. Irrigation Rate

The main effect of the irrigation rate on yield was significant for three of the five site-years (Logan 2019, Vernal 2021, and Cedar City 2021). The full irrigation rate for each of these site-years produced the greatest yields. In Logan 2019, the 75% rate was statistically similar to the 100% rate and the uniform 50% rate (Figure 5). The uniform 50% rate reduced yield by 9% compared to full irrigation, and the targeted deficit rate (average of 75% irrigation over the growing season) performed the worst, yielding a 23% lower outcome than the 100% treatment. Targeting the irrigation application did not provide a benefit over either of the uniform reductions, as it yielded an 18% lower outcome than the uniform 75% rate and an 11% lower outcome than the uniform 50% rate. Vernal in 2021 showed a split between two sets of treatments, with the 100% rate and 75% rate performing statistically similar and the 50% uniform reduction and the targeted reduction (average of 81% irrigation over the season) performing statistically similar (Figure 6). Compared to the 100% rate, yield was reduced by 52% with the 50% rate and 36% with the 81% targeted rate. For Cedar City in 2021, any reduction in irrigation reduced yield significantly, as the 75% rate lowered yield by 18%, the 50% uniform rate lowered yield by 30%, and the 61% targeted rate lowered yield by 24%. These results illustrated that irrigation cuts did not always provide a proportionate yield loss, and that deficit irrigation did not always reduce silage corn yield. Some of the lack of response could have been due to imperfect estimates of evapotranspiration to schedule irrigation and restrictions of irrigation timing that could not be avoided. The study results are evidence that targeted deficit irrigation did not improve silage corn yield above unform irrigation reductions.

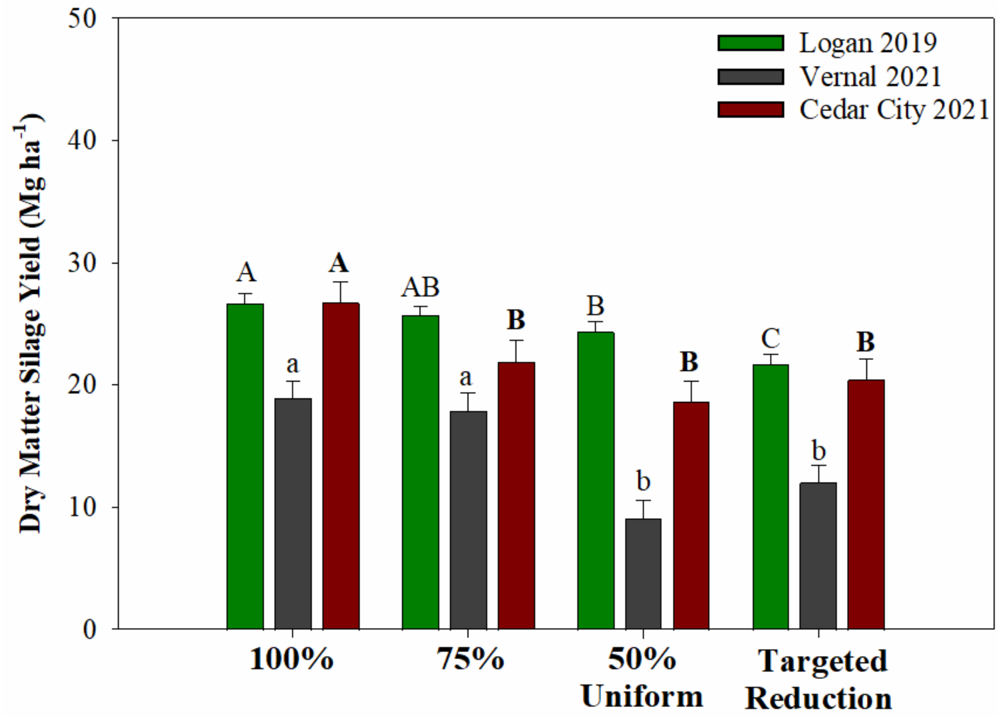

Figure 6. Silage corn yield at four irrigation rates that included 100, 75, and 50% of estimated evapotranspiration, along with a targeted reduction at 50–87% of estimated evapotranspiration (target was 50%, but it varied with year; Table 2). The 75% and 50% rate treatments were uniform reductions of every irrigation. The targeted reduction was adjusted to apply more irrigation at critical crop stages and no or less irrigation at other times. Error bars represent standard errors. Letters above bars represent mean separations conducted by site-year with protected Fisher's LSD at $\alpha = 0.05$. Letter format designates mean separation for each site-year, with uppercase as one and lower case as the other.

3.3. Silage Corn Forage Quality

Unlike some other forages, silage corn quality values do not have standard quality ranges that are used for marketing silage corn, because it is often fed on farm or sold to a nearby farm by weight and not quality. However, forage quality of silage corn is important for balancing rations on the farm, especially for dairy cattle. Six quality parameters were selected for comparison in this study and included ADF, NDF, CP, starch, TDN, and NDFD48. Lower ADF and NDF values indicate higher forage quality through improved feed consumption, and elevated CP, starch, TDN, and NDFD48 are considered higher quality, as they improve nutrition and digestibility of the forage.

3.3.1. Irrigation Technology × Genetics

The interaction between irrigation technology and crop genetics only influenced ADF and TDN, and for these, only for three of five site-years (Supplemental Table S1). At Logan in 2019, silage corn ADF was the lowest and more favorable among the treatments that yielded the least—LESA with non-DT corn and LENA with DT corn. The highest, most unfavorable, ADF value (21.2%) occurred in the highest-yielding treatment of MESA and DT genetics. Similarly, in 2020 at the Vernal site, the lowest-yielding system (MDI) with both genetics produced more favorable (i.e., lower) ADF values than other irrigation systems. Though yield was not significantly affected by the interaction of technology and genetics in Logan 2020 (Table 3), the TDN values were greater with non-DT corn compared to the DT corn in all irrigation systems except MESA. The largest difference in TDN among irrigation systems occurred in LEPA, in which the non-DT hybrid had 17% more TDN than the DT hybrid. In MESA, the DT hybrid had greater TDN than the non-DT hybrid (24.1% versus 23.6%). These collective results from the three sites indicate that few benefits in silage corn quality were present with DT genetics. The DT hybrids had equivalent CP, starch, NDF, and NDFD48 as the non-DT hybrids in most cases and often more ADF and less TDN. Benefits of DT hybrids on silage quality were sometimes more prevalent with MESA than other systems, which corroborates the yield results that indicate that DT genetics may do best with MESA.

3.3.2. Irrigation Rate × Genetics

The irrigation rate and genetics interaction were only significant for Logan and Vernal in 2020 (Supplemental Table S2). Acid detergent fiber, NDF, and starch were impacted at both sites, and CP was also impacted in Vernal in 2020. Crude protein levels generally declined as irrigation decreased for both hybrids in Vernal in 2020. The DT hybrid maintained CP levels at the 100% and 50% irrigation rates but had CP levels that were 1.3 and 2.6 percentage points greater than the non-DT hybrid for the 75% and targeted 50% rates, respectively. These results demonstrate that the DT hybrid can sometimes improve CP under deficit irrigation. However, the benefit was not consistent, because DT genetics only improved CP at one site-year, and not all the deficit irrigation rates had elevated CP with DT genetics.

The impacts of irrigation rate × crop genetics on ADF and NDF values were somewhat consistent at Logan and Vernal in 2020 (Supplemental Table S3). Drought-tolerant genetics had elevated ADF (lower forage quality) at a single irrigation rate at each site. The DT hybrid had 2.8 or 2.3 percentage points more ADF than the non-DT hybrid in the full irrigation at Logan and the targeted 50% rate in Vernal, respectively. By contrast, the DT hybrid decreased NDF by 0.53, 0.44, and 1.8 percentage points compared to the non-DT hybrid at the 100% and 50% rates in Logan and the 50% targeted rate in Vernal, respectively. These cumulative results indicate that DT hybrids may reduce NDF and improve feed quality for some full and deficit irrigation rates, but the benefits were not consistent.

Starch levels never increased with DT genetics in Logan in 2020, and starch decreased by 6.1 percentage points with DT corn compared to non-DT corn at the 75% irrigation rate. By contrast, starch levels increased by 3.2 and 4.2 percentage points for DT corn vs. non-DT corn in the 75 and 50% targeted irrigation rates, respectively, for Vernal 2020. These results were consistent with CP, ADF, and NDF and are evidence that DT genetics rarely and inconsistently impacted silage quality at full or deficit irrigation rates. The most consistent benefit observed among sites with DT genetics was reduced NDF at some of the deficit irrigation rates.

3.3.3. Irrigation Technology

All five site-years had at least one feed quality parameter affected by the main effect of irrigation technology (Supplemental Table S4). However, the impacts of irrigation technology on forage quality varied by site and by year. The most inconsistent response to the various forage parameters occurred at the Logan site. In 2019, with the abnormally wet spring, LEPA decreased forage quality with greater NDF (8.7% vs. 8.2%) than all four other systems and less TDN (21.8% vs. 24.9%) than all systems besides LESA (23.6%). This was not the case in the drier year of 2020. Few consistent differences in quality occurred among systems for this site. The MDI and LENA produced the most favorable ADF values, LESA and LENA the most favorable NDF, and LESA, MDI, and LEPA the greatest NDFD48 values. These results did indicate that the alternative irrigation systems often but sporadically improved silage quality parameters at this site in a year with average spring rainfall and greater irrigation needs. Corn in Vernal in both years was heavily stressed by low spring precipitation and limited irrigation, with the 2021 growing season being shortened to mid-July due to drought. The largest and most consistent difference among systems at this site were for the MDI compared to the other three systems that were often equivalent or similar. The MDI system had on average 1.5% points more NDF and 5% points less TDN than other systems in both years (Supplemental Table S5). More forage parameters were influenced in 2021, and MDI provided quality improvements, excluding the much lower ADF (6.2% vs. 10.1–14.4%), which included 3% points greater starch content than the other three systems. As mentioned previously, MDI irrigation rates were often restricted due to filtration challenges. Water stress was evident in this system at Vernal. Extreme water stress sometimes provided forage quality benefits, but this came with a sacrifice of yield. Irrigation technology at the Cedar City site in 2021 had consistent effects on silage corn quality parameters—MESA stressed the corn and did not yield as high an output as the three low-elevation systems and subsequently almost always (except NDF) had different forage quality (data not shown). At this site, MESA improved some aspects of forage quality (CP and starch were 13% higher, ADF was 37% lower) but decreased other aspects (TDN and NDFD48 were 19% lower) compared to all three low-elevation systems. The quality improvements with MESA were a result of lower yield with MESA and less fibrous and more digestible forage. However, this came at a significant yield loss and indicates that MESA did not perform as well as other systems in a windy area with comparatively coarse soils.

3.3.4. Irrigation Rate

The irrigation rate impacted silage corn CP, ADF, and NDFD48 (Supplemental Table S6) at three site-years (Logan 2019, Vernal 2021, and Cedar City 2021). The other three quality parameters (NDF, starch, and TDN) were also impacted by the irrigation rate at one or two of these same three site-years. Crude protein was the greatest in the 100% treatment in 2019 in Logan (25.6%) and decreased by 0.86% points with the 75% rate, 1.6% points with the 75% targeted rate, and 1.8% points with the 50% rate. Vernal in 2021 had the greatest CP with the 75% irrigation rate (25.1%) and decreased by 5% with the 100% rate, 10% with the 50% rate, and 5% with the targeted 81% rate. The targeted rate was not as severely stressed nor as properly timed due to water restrictions for the site-year, making the comparison more challenging. Cedar City in 2021 also had the greatest CP level, in the 75% rate (22.4%), with reductions in the other treatments of 8% for the 100% rate, 5% for the 50% rate, and 12% with the targeted 61% rate. The relatively consistent results across these three site-years are evidence that deficit irrigation often reduced CP, and targeting the deficit did not improve CP levels.

The impact of the irrigation rate on ADF was relatively consistent at the three responsive site-years (Logan 2019, Vernal and Cedar City 2021). The 100% irrigation rate resulted in the greatest, most unfavorable ADF, and irrigation reductions decreased ADF. For two of the site-years (Vernal and Cedar City 2021), the 50% reduction resulted in the best ADF values, which were 7.6 and 6.3 percentage points lower than the 100% treatment, respective to site-years. Uniformly decreasing the irrigation rate was often better (lower ADF) than targeting rate reductions, except in Logan 2019, where the 75% targeted rate performed the best with 3.1% points less ADF than the 75% uniform rate. As was the case with ADF, the response of NDFD48 to the irrigation rate was similar across the three responsive site-years. The highest NDFD48 values for Logan 2019 and Logan 2020 were produced with the uniform 50% rate and targeted deficit rates, which were statistically similar. The Cedar City 2021 site-year had the targeted 61% treatment produce the highest NDFD48 value. For two of the three site-years, the NDFD48 values were higher under larger irrigation deficits (50% vs. 75%).

Silage corn NDF values were affected by the irrigation rate in Logan in 2019 and Vernal in 2021 (Table 3), with the 50% uniform rate producing the largest, or least favorable values, and greater irrigation rates causing slight decreases in NDF. The best NDF values were produced in the 100% rate, but they were often statistically similar to the other rates. The most unfavorable values were produced in both site-years by the uniform 50% rate. Targeting the reduction did not positively affect the parameter over a simple reduction over the season.

Starch values were the highest with both the 75 and 50% uniform rates in Vernal 2021 and Cedar City 2021 compared to the full irrigation or targeted reductions (Supplemental Table S7). Starch increased by 3.4% points in Vernal 2021 and 3.3% points in Cedar City 2021 with the 100% rate vs. the 75% rate. The targeted irrigation rate reductions produced less starch than the uniform reductions, though it was hard to make a full comparison, as the rates did not equal either of the seasons' uniform reductions. Further, silage corn TDN was affected by the irrigation rate only in Vernal in 2021, where TDN was greatest at the full irrigation rate and decreased by 4.3, 5.9, and 4.6% points with the 75%, 50%, and 87% targeted irrigation rate treatments, respectively. Results illustrated a common feed of more favorable feed quality parameters under more stress-inducing factors such as reduced irrigation rates, but the differences were not proportionate to the decreases in irrigation amounts. Silage CP values tended to be lower in irrigation rate reductions, as there is a correlation between nitrogen uptake and irrigation rates, and nitrogen is the key nutrient needed for protein production.

3.3.5. Genetics

Crude protein was affected by genetics in Logan 2020 and Vernal 2021 (Supplemental Table S8), with DT producing greater CP than the non-DT (0.6% and 2.1% point difference, respectively, for each year). Silage NDF values were affected in Vernal 2021 and Cedar City 2021, with the lower, more favorable value produced by the DT genetics (1 and 0.54% point difference, respectively). Starch values were affected by genetics in Vernal 2021, where the DT produced 1.2 percentage points more starch compared to the non-DT. Silage TDN was affected in Logan and Vernal in 2020, where both sites had non-DT producing 2.3 or 2.7% points more TDN than the DT hybrids, respectively (Supplemental Table S9). The values of NDFD48 were affected by corn genetics in Vernal 2021, with the non-DT hybrid producing 1.4 percentage points more NDFD48 than the DT hybrid. These results indicated that DT genetics had no consistent silage corn quality improvements across site-years and parameters.

4. Discussion

4.1. Combinations of Irrigation Technologies, Rate, and Crop Genetics on Corn Silage Yield

One purpose of this study was to examine how interactions between an irrigation system, the irrigation rate, and crop genetics impact silage corn production, and whether there were any cumulative water optimization benefits when combining or stacking several factors. Due to the restricted experimental design, we were not able to test three-way interactions of the irrigation system, rate, and crop genetics. The interactions and main effects that we were able to test demonstrated that the irrigation rate had the greatest effect on yield, followed by irrigation systems, and then drought-tolerant genetics. These results suggest that the greatest potential for water optimization, while maintaining yield, would likely involve refining irrigation rates to best match the full evapotranspiration demand of silage corn. Further, the results also indicated that few benefits were observed for targeted deficit irrigation and drought-tolerant genetics in the alternative irrigation systems. Drought-tolerant genetics may be a feasible and inexpensive way to improve water utilization in MESA sprinkler systems, in which irrigation application efficiencies are lower than low-elevation systems.

Collective results from the five site-years indicate that alternative irrigation systems (LEPA, LESA, LENA) can often improve silage corn yield, but that the results are weather and site dependent. The MDI irrigation technology never improved the yield in any site-year during the study. This indicates that caution should be used when designing and installing various irrigation systems to ensure that the ideal system is selected. The advanced systems together were statistically different than the MESA in Cedar City. Much of the benefit of these alternative systems was likely due to improved irrigation uniformity resulting from closer nozzle spacing within the crop canopy. Peters et al. (2015) found in testing of LESA systems in the Pacific Northwest that they applied irrigation more uniformly than MESA in corn.

In contrast to some of our results, a Kansas study compared corn grain yield with MDI, LEPA, and LESA and noted no significant differences in yield, suggesting the water savings were worth the MDI use [10]. The MDI system in our study did not perform as well as the sprinkler systems in all cases. Despite the installation of automated fine-screened filters and periodic chemical treatment of the water with highly concentrated chlorine, the MDI system flow rates were consistently lower than the design rates. These filtration issues were likely the main reason why MDI often reduced corn yield. Growers interested in utilizing MDI should carefully consider filtration challenges and plan accordingly. Further, additional studies are needed to identify site-specific conditions needed to optimize the use of LEPA, LESA, LENA, and MDI. Key differences between our study and previous research include the use of a lateral-move system to eliminate pressure differences that occur with a center pivot between towers and drops and to compare the more advanced sprinklers with one another and the grower standard.

The interaction between the irrigation system and rate was critical to examining whether low-elevation nozzles or MDI could reduce irrigation requirements compared to MESA due to their higher irrigation application efficiencies. This has rarely been examined in irrigation system studies. We attempted to examine this, but the statistical design was limited due to logistical challenges of replicating systems and rates when utilizing farm-scale irrigation systems necessary for this type of testing. This limitation necessitated that the interaction between the system and rate be considered a random effect. Despite this, numerical examinations showed that the low-elevation and MDI systems at the 75% irrigation rate could often maintain the yield of the full irrigation rate of MESA. Future testing should examine replicated interactions of irrigation systems and rates to verify when and how much irrigation rates can be reduced for low-elevation sprinklers and MDI.

There have been several studies that compare DT varieties to their conventional counterpart, but few have been conducted in semi-arid conditions of the Western United States and with various irrigation rates. In Kansas, researchers found DT corn commonly increased yield compared to non-DT under both 100% and 50% irrigation rates in a silt loam soil, though the increases (around 50 kg ha^{-1}) were minimal [23]. A three-year study in Mississippi compared two types of DT hybrids (DroughtGard® and AQUAmax) and found that the yield benefit varied from year to year, and that irrigation stress did not affect yield components [24] (Bruns, 2019). The present study confirms the variation in previous studies and indicates that additional studies are needed to identify the infrequent conditions under which DT hybrids improve yield in drought conditions, so that more site-specific recommendations can be provided to growers.

Contrasting our study, researchers in Colorado found that stage-based (late vegetative vs. during maturation or both) deficit irrigation influenced corn grain yield and yield components [14]. In their study, deficit irrigation during maturation was more detrimental to yield than during late vegetative stages, and the combination of deficit irrigation in both stages decreased yield the most. They concluded that deficit irrigation should be targeted to late vegetative stages, and available irrigation should be targeted to maturation stages. Our targeted deficit was similar to their approach, in which corn was stressed most during early vegetative stages and then at medium stress levels during late vegetation with full irrigation during maturation stages. However, our results indicated no benefit of the targeted stress compared to a uniform deficit all season. The difference in response between our study and [14] could be related to harvest type (grain vs. silage) and dry matter partitioning. In Nebraska, a study showed that deficit irrigation during the corn maturation stage affected grain and cob yield but not stover [30]. Further, these authors observed that optimal targeted deficit irrigation strategies varied by year and concluded that flexible targeted deficit irrigation should be utilized. Our results for silage corn in the Western United States indicated that targeting deficit irrigation for silage corn was never superior to uniform deficits. This being the case, deficit irrigation strategies could be simplified to uniform reductions rather than a targeted deficit, which would be easier to implement by growers.

However, the benefit of DT genetics was not realized in more efficient irrigation systems or with deficit irrigation. In general, the drought-tolerant variety tested in our study has not been historically the one tested by others, as DroughtGuard® is a transgenic type compared to the traditionally bred AQUAmax ® and other similar varieties [16–18]. Many of these studies denote the differences in varieties, often improving yields, but due to elevation, soil type, calcareous nature, and ET requirements, these comparisons are more difficult to make across studies.

4.2. Combinations of Irrigation Technology, Rate, and Crop Genetics on Corn Silage Feed Quality Parameters

Studies focusing on silage corn production are limited in scope due to the limitation of hectares focused on silage cornproduction, as grain corn production dominates hectares and research. Many studies looking at the various effects on grain corn production take final yield and grain formation values that are not comparable to silage due to crop maturation. Biomass measures are often made in these grain studies, but they do not often offer an equal comparison to full season biomass compared to stage-based values [14,23–25].

In general, there were not frequent, large, or consistent differences in silage corn quality parameters due to irrigation system, rate, or crop genetic treatments. Similar to yield responses, there were rarely high-level treatment interactions that affected feed quality parameters. The overall percent change for each parameter by factor were not consistent among site-years. All the tested quality parameters were less affected by crop genetics than the other factors, and the large range in forage quality changes with irrigation technology or rate often came from Vernal in 2021. This site-year has been mentioned previously as the one in which irrigation was not possible beyond halfway through the season due to drought. In these extreme cases of water shortages, the quality often increases, but the yield decreases substantially. This occurred in Vernal in 2021, and the silage corn quality increases did not counter the value of the yield loss.

5. Conclusions

This research is the beginning of a long-term study to test the interacting effects of irrigation systems, irrigation rates, and crop genetic treatments on silage corn production. The results from the five site-years presented here are evidence that there was not a water-saving technology that could always maintain silage corn yield and quality in all settings. Furthermore, irrigation technologies, irrigation rates, and drought-tolerant genetics have site-specific effects on corn production. The irrigation rate was the most common factor that affected yield and feed quality parameters. The rate often had the largest negative impact on yield. The reduction in rate often improved feed parameters, with less lignin produced by smaller, stressed plants. However, these improvements would rarely justify the yield loss. Targeted deficit irrigation was rarely superior to a uniform deficit irrigation, supporting this research's finding that the simpler uniform deficit irrigation might be suitable during drought and in cases in which water is limited.

Drought-tolerant hybrids provided the most yield and forage quality benefits in the MESA irrigation system. However, there were few and inconsistent benefits of DT genetics across site-years at full or at reduced irrigation rates. This suggests that irrigation system and rate changes have much larger impacts on corn water optimization than crop genetics. Further, the benefits of DT hybrids may lessen as more efficient irrigation systems are used. However, the combination of DT genetics and MESA irrigation technology could be a more affordable option in terms of upfront capital if the MESA technology is already part of the production system.

The three low-elevation systems (LEPA, LESA, and LENA) were similar in yield to MESA, though only statistically better in one site-year. The forage quality was inconsistent and rarely improved with these advanced systems. No clear advantages were observed for a single low-elevation system, as many performed the same or inconsistently benefited yield or quality parameters among site-years. The MDI system often yielded less and had better forage quality than the other systems, which was likely due to the restricted flow rates from inadequate filtration and chemical treatment.

Our experiment was designed to minimize yield and quality losses while implementing various water-saving practices. Results to date indicate that refining irrigation rates and utilizing more efficient sprinkler technologies have the greatest potential to maintain production with less applied water. Additional years of this study will lead to a better understanding of not only the combinations of these practices but also the long-term effect of prolonged use. Furthermore, impacts of irrigation technology, irrigation rate, and crop genetics on water use, nutrient use, and energy use efficiencies will also be examined.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13051194/s1. Table S1: Irrigation Technology and Genetics Significant Interactions on Corn Quality; Table S2: Irrigation Rate and Genetics Significant Interactions on Corn Quality—P1; Table S3: Irrigation Technology and Genetics Significant Interactions on Corn Quality—P2; Table S4: Irrigation Technology Significance on Corn Quality—P1; Table S5: Irrigation Technology Significance on Corn Quality—P2; Table S6: Irrigation Rate Significance on Corn Quality—P1; Table S7: Irrigation Rate Significance on Corn Quality—P2; Table S8: Crop Genetics Significance on Corn Quality—P1; Table S9: Crop Genetics Significance on Corn Quality—P2.

Author Contributions: Conceptualization, M.A.Y. and T.S.; methodology, M.A.Y. and T.S.; formal analysis, T.S.; data curation, D.B.; writing—original draft preparation, T.S.; writing—review and editing, M.A.Y., E.C., B.K., R.V. and B.B.; visualization, T.S.; project administration, M.A.Y.; funding acquisition, M.A.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was made possible by support from a Utah State University (USU) Extension Water Initiative Grant, a Foundation for Food and Agriculture Young Scholar Award, and a Sustainable Agriculture Research and Education Grant.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are presented within the article.

Acknowledgments: The authors also acknowledge the extensive assistance provided by county Extension agents, farm managers, USU graduate and undergraduate students, and Extension specialists.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Dieter, C.A.; Maupin, M.A.; Caldwell, R.R.; Harris, M.A.; Ivahnenko, T.I.; Lovelace, J.K.; Barber, N.L.; Linsey, K.S. *Estimated Use of Water in the United States in 2015 (Circular 1441)*; U.S. Geological Survey: Reston, VA, USA, 2017. [CrossRef]
2. Garrick, D.; De Stefano, L.; Yu, W.; Jorgensen, I.; O'Donnell, E.; Turley, L.; Aguilar-Barajas, I.; Dai, X.; de Souza Leao, R.; Punjabi, B.; et al. Rural water for thirsty cities: A systemic review of water reallocation from rural to urban regions. *Environ. Res. Lett.* **2019**, *14*, 043003. [CrossRef]
3. Scott, M. National Climate Assessment: Great Plains' Ogallala Aquifer Drying out. NOAA Climate.gov. 2019. Available online: https://www.climate.gov/news-features/featured-images/national-climateassessment-great-plains-ogallala-aquifer-drying-out (accessed on 13 December 2021).
4. Vogel, E.; Donat, M.G.; Alexander, L.V.; Meinshausen, M.; Ray, D.K.; Karoly, D.; Meinshausen, N.; Frieler, K. The effects of climate extremes on global agricultural yields. *Environ. Res.* **2019**, *14*, 054010. [CrossRef]
5. Ali, M.H.; Talukder, M.S.U. Increasing water productivity in crop production—A synthesis. *Agric. Water Manag.* **2008**, *95*, 1201–1213. [CrossRef]
6. Hatfield, J.L.; Sauer, T.J.; Prueger, J.H. Managing soils to achieve greater water use efficiency. *Agron. J.* **2001**, *93*, 271–280. [CrossRef]
7. Varshney, R.K.; Bansal, K.C.; Aggarwal, P.K.; Datta, S.K.; Craufurd, P.Q. Agricultural biotechnology for crop improvement in a variable climate: Hope or hype? *Trends Plant Sci.* **2011**, *16*, 363–371. [CrossRef]

8. Amosson, S.; Almas, L.; Girase, J.; Kinney, N.; Guerrero, B.; Vinlesh, K.; Marek, T. *Economics of Irrigation Systems*; B-6113; Texas AgriLife Extension Service: College Station, TX, USA, 2011; 14p.
9. Kisekka, I.; Oker, T.; Nguyen, G.; Aguilar, J.; Rogers, D. Revising precision mobile drip irrigation under limited water. *Irrig. Sci.* **2017**, *35*, 483–500. [CrossRef]
10. Oker, T.E.; Kisekkab, I.; Sheshukova, A.Y.; Aguilara, J.; Rogers, D.H. Evaluation of maize production under mobile drip irrigation. *Agric. Water Manag.* **2018**, *210*, 11–21. [CrossRef]
11. Peters, R.T.; Neibling, H.; Stroh, R.C. Testing Low Energy Spray Application (LESA) in the Pacific Northwest. In Proceedings of the 2015 ASABE/IA Irrigation Symposium: Emerging Technologies for Sustainable Irrigation. Conference Proceedings, Long Beach, CA, USA, 10–12 November 2015. [CrossRef]
12. Sarwar, A.; Peters, R.T.; Mehanna, H.; Amini, M.Z.; Mohamed, A.Z. Evaluating water application efficiency of low and mid elevation spray application under changing weather conditions. *Agric. Water Manag.* **2019**, *221*, 84–91. [CrossRef]
13. Kranz, W.L.; Irmak, S.; Van Donk, S.M.; Yonts, C.D.; Martin, D.L. *Irrigation Management for Corn*; G1850; University of Nebraska Extension: Lincoln, NE, USA, 2008. Available online: https://extensionpublications.unl.edu/assets/pdf/g1850.pdf (accessed on 15 May 2019).
14. Zhang, H.; Han, M.; Comas, L.H.; DeJonge, K.C.; Gleason, S.M.; Trout, T.J.; Ma, L. Response of maize yield components to growth stage-based deficit irrigation. *Agron. J. Climatol. Water Manag.* **2019**, *111*, 3244–3252. [CrossRef]
15. Manning, D.T.; Lurbe, S.; Comas, L.H.; Trout, T.J.; Flynn, N.; Fonte, S.J. Economic viability of deficit irrigation in the Western US. *Agric. Water Manag.* **2018**, *196*, 114–123. [CrossRef]
16. McFadden, J.; Smith, D.; Wechsler, S.; Wallander, S. *Development, adoption, and management of drought-tolerant corn in the United States*; USDA Economic Information Bulletin Number 204; United States Department of Agriculture, Economic Research Service: Washington, DC, USA, 2019; pp. 1–39.
17. Jin, Z.; Qing-wu, X.; Jessup, K.E.; Xiao-bo, H.; Bao-zhen, H.; Marek, T.H.; Wenwei, X.; Evett, S.R.; O'Shaughnessy, S.A.; Brauer, D.K. Shoot and root traits in drought tolerant maize (*Zea mays* L.) hybrids. *J. Integr. Agric.* **2018**, *17*, 1093–1105.
18. Sammons, B.; Whitsel, J.; Stork, L.G.; Reeves, W.; Horak, M. Characterization of drought-tolerant maize MON 87460 for use in environmental risk assessment. *Crop Sci.* **2014**, *54*, 719–729. [CrossRef]
19. Tollefson, J. Drought-tolerant maize gets US debut. *Nature* **2011**, *469*, 144. [CrossRef] [PubMed]
20. Zheng'e, S.; Zhao, J.; Marek, T.H.; Liu, K.; Harrison, M.T.; Xue, Q. Drought tolerant maize hybrids have higher yields and lower water use under drought conditions at a regional scale. *Agric. Water Manag.* **2022**, *274*, 107978. [CrossRef]
21. Cooper, M.; Gho, C.; Leafgren, R.; Tang, T.; Messina, C. Breeding drought-tolerant maize hybrids for the US corn-belt: Discovery to product. *J. Exp. Biol.* **2014**, *65*, 6191–6204. [CrossRef] [PubMed]
22. Harrigan, G.G.; Ridley, W.P.; Miller, K.D.; Sorbet, R.; Riordan, S.G.; Nemeth, M.A.; Reeves, W.; Pester, T.A. The forage and grain of MON 87460, a drought-tolerant corn hybrid, are compositionally equivalent to that of conventional corn. *J. Agric. Food Chem.* **2009**, *57*, 9754–9763. [CrossRef] [PubMed]
23. Adee, E.; Roozeboom, K.; Balboa, G.R.; Schelegel, A.; Ciampitti, I.A. Drought-tolerant corn hybrids yield more in drought-stressed environments with no penalty in non-stressed environments. *Front. Plant Sci.* **2016**, *7*, 1534. [CrossRef]
24. Bruns, H.A. Comparison of yield components and physiological parameters of drought tolerant and conventional corn hybrids. *Agron. J. Crop Ecol. Physiol.* **2019**, *111*, 565–571. [CrossRef]
25. Hao, B.; Marek, T.H.; Jessup, K.E.; Becker, J.; Hou, X.; Xu, X.; Bynum, E.D.; Bean, B.W.; Calaizzi, P.D.; Howell, T.A. Water use and grain yield in drought-tolerant corn in Texas High Plains. *Agron. J.* **2015**, *107*, 1922–1930. [CrossRef]
26. O'Geen, T. *SoilWeb*; University of California-Davis: Davis, CA, USA, 2022. Available online: https://casoilresource.lawr.ucdavis.edu/gmap/ (accessed on 23 October 2020).
27. Peters, T.; Hill, S. Irrigation Scheduler Mobile. Washington State University Extension. 2022. Available online: http://weather.wsu.edu/ism/index.php?m=1 (accessed on 30 April 2019).
28. Cardon, G.; Jotuby-Amacher, J.; Hole, P.; Koenig, R. *Understanding Your Soil Test Report*; Utah State University Extension; AG/Soils/2008-01pr; Utah State University: Logan, UT, USA, 2008.
29. Clark, J.D.; Yost, M.A.; Griggs, T.C.; Cardon, G.E.; Ransom, C.V.; Creech, J.E. Nitrogen fertilization and glyphosate-resistant alfalfa termination method effects on first-year silage corn. *Agron. J.* **2021**, *113*, 1712–1723. [CrossRef]
30. Payero, J.O.; Tarkalson, D.D.; Irmak, S.; Davison, D.; Petersen, J.L. Effect of timing of a deficit-irrigation allocation on corn evapotranspiration, yield, water use efficiency and dry mass. *Agric. Water Manag.* **2009**, *96*, 1387–1397. [CrossRef]