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Hemp Seed Yield Responses to Nitrogen Fertility Rates

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Abstract: Industrial hemp (*Cannabis sativa* L.) holds promise as a crop for more sustainable supply chains given its potential as a source of high-strength fibers, adsorbents, and nutrient-dense feedstuffs. Developing nutrient management guidelines for hemp will be an important part of optimizing the crop's sustainability attributes. This study measured hemp seed yield in response to N fertilization rate (0, 60, 120, 180, and 240 kg N ha^{-1}). Treatments were tested with four hemp cultivars ('Joey' and 'Grandi' in 2020, 2021, and 2022 and 'NWG 2463' and 'NWG 4113' in 2023) in Virginia. Nitrogen input influenced ($p \leq 0.0177$) seed yield in all four experimental years, although the pattern of response varied substantially. In 2020, following delayed seeding, hemp showed a weak quadratic ($p = 0.0113$) response to N inputs, with peak yield (1640 kg ha^{-1}) occurring with 120 kg N ha^{-1}. In 2021, hemp displayed a strong linear ($p < 0.0001$) response to N inputs, with the highest seed yield (2510 kg ha^{-1}) at 240 kg N ha^{-1}. In 2022, a season characterized by low precipitation and high weed pressure, a weak, linear ($p = 0.0111$) response to the N rate was observed. The greatest seed yield (380 kg ha^{-1}) was again observed with 240 kg N ha^{-1}. In 2023, weed pressure remained an issue, but the response to N was strong and linear ($p < 0.0001$), with the greatest seed yield (831 kg ha^{-1}) again measured at 240 kg N ha^{-1}. These findings indicate hemp can be quite responsive to N inputs but that the magnitude of response is sensitive to other factors such as available soil moisture, weed pressure, and growing period.

Keywords: nitrogen rates; biomass yield; hemp seed yield; plant height; nutrient management

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1. Introduction

Industrial hemp is a promising crop for more sustainable supply chains. With appropriate management, it has high productivity in the sense of high carbon accretion with moderate inputs [1]. Integration into existing cropping systems will support greater farm system diversity and afford the opportunity to produce several types of harvested products (e.g., seed, fiber, and essential oil). These products have potential uses across numerous markets, including food, feed, insulation, absorbents, building materials, and medicinal and healthcare products [2].

Efficient and sustainable crop production is essential to meet the world's growing demands for food and other agricultural products [3]. In this context, appropriately managing nutrients is one of the important agronomic conditions to meet when establishing economically and ecologically viable cropping systems [3]. With hemp, nutrient input needs can vary significantly depending on production system outputs (i.e., fiber vs. seed vs. flowers), cultivars, geographic location, and soil conditions [4]. Previous cropping history and soil nutrient condition also must be taken into account to avoid over-application of nutrients and optimize inputs.

As the nutrient often most limiting in cropping systems [3], nitrogen (N) plays a crucial role in supporting crop yield and quality. However, N fertility management is critical to environmentally healthy and economically sound production systems. Nitrogen fertilizers are energetically expensive, excessive application of N can lead to environmental pollution and substantial greenhouse gas emissions, and inadequate N can limit yield and cause economic losses [3,5]. Thus, it is essential to develop crop-specific N fertilizer management guidelines.

Typical N recommendations for hemp production vary by production system. Suggested rates for fiber have ranged from 50 to 100 kg ha^{-1}, although positive responses have been observed at rates as high as 240 kg N ha^{-1} [6]. Seed production systems generally require more nitrogen than fiber production, with recommendations ranging from 100 to 150 kg ha^{-1} [7,8]. Aubin et al. [9] observed a positive, linear response to N at rates up to 200 kg ha^{-1} in Québec, Canada, and did not detect a maximum rate for seed yield. Papastylianou et al. [6] observed that the application of 240 kg N ha^{-1} resulted in significantly greater biomass yield, stem dry weight, and inflorescence weight in Athens, Greece.

Research conducted in Québec, Canada, demonstrated that applying 200 kg N ha^{-1} significantly increased biomass and seed yields across different cultivars and environments [9]. Biomass yield rose from 1670 to 4210 kg ha^{-1}, while seed yield increased from 520 to 1340 kg ha^{-1} [9]. However, under Mediterranean conditions in central Italy, Campiglia et al. [10] discovered that higher N fertilization levels (100 kg N ha^{-1}) contributed more to stem yields (28% increase), while inflorescence and seed yields were less affected (17% and 4%, respectively) when compared with 50 kg N ha^{-1} for seven different European-originated genotypes. These findings highlight that hemp plants have variable responses to N fertilizer based on sites, cultivars, environments, soil types, etc., and indicate that addressing hemp nutritional requirements will require more site-specific research in various soil types and production systems.

In the southeastern US, hemp cultivation holds historical significance dating back to the region's early settlement [11]. During the colonial period, hemp was a crucial crop due to its versatile uses, including fiber for textiles, oil for lamps, and seeds for food [12]. Over time, the cultivation of hemp declined, but recent years have seen a resurgence of interest in hemp, particularly for its potential in various industries such as textiles, CBD production, and grain production [11]. Southwest Virginia features diverse climates and soil types, influencing agricultural practices. The region's topography, precipitation patterns, and temperature variations play a role in crop success [13]. Understanding the optimal conditions for hemp grain production, including the appropriate nitrogen rates, is essential for maximizing yields and ensuring sustainable farming practices in this specific environment. The aim of this study was to measure hemp plants' response to different rates of N fertility.

2. Materials and Methods

2.1. Study Sites

The study was conducted at the Virginia Tech Urban Horticulture Center (37°13′05″ N, 80°27′52″ W, 616 m elevation) in 2020 and 2021 and the university's Kentland Farm (37°11′43″ N, 80°34′47″ W, 528 m elevation) in 2022 and 2023, both located in Blacksburg, VA, USA. Soils at the Urban Horticulture Center are Duffield Ernest complex (fine-loamy, mixed, active mesic Ultic Hapludalfs and fine-loamy, mixed, superactive, mesic Aquic Fragiudults). Soils at Kentland are Unison and Braddock (fine, mixed, semiactive, mesic Typic Hapuldults). Before seeding, the soil had total nitrogen levels of 0.37%, 0.43%, 0.61%, and 0.82%, and soil C:N ratios of 6.04, 4.47, 4.35, and 2.66 in 2020, 2021, 2022, and 2023, respectively.

2.2. Experimental Design

The experiment was conducted as a randomized complete block design with a split-plot treatment arrangement and four replicates. The main plots were the two selected cultivars and the sub-plots were the five N fertilizer treatments (i.e., 0, 60, 120, 180, and 240 kg N ha^{-1}).

2.3. Hemp Establishment

Two industrial hemp cultivars ('Joey' and 'Grandi' in 2020, 2021, and 2022, and 'NWG 2463' and 'NWG 4113' in 2023) were established during each test year. Studies of Grandi and Joey allowed the comparison of hemp types with differing morphology; Grandi is grown primarily for oilseed while Joey is a dual-purpose cultivar, allowing for the harvest of both seed and fiber. Both Grandi and Joey originated in Canada. The inability to obtain seeds of these cultivars in 2023 led to the use of NWG 2463 and NWG 4113, which are both US-originated dual-purpose cultivars.

Main plots (cultivars) were randomized within each replicate (R = 4) and planted with a commercial, no-till drill in all years. Seeds were planted into no-tilled killed grass sod in 2020 and 2021 and into a tilled, fallow field in 2022 and 2023. Target seeding depth was 1 cm. Row spacing was 30 cm in 2020 and 2021 (four rows per plot) and 19 cm (nine rows per plot) in 2022 and 2023. Seeding rate for each cultivar was 28 kg ha^{-1}. Seeding events occurred on 19 June 2020, 13 May 2021, 17 May 2022, and 26 May 2023. The seeding date was delayed in 2020 due to high soil moisture early in the season.

2.4. Subplot Establishment and Maintenance

To minimize effects of stand variability, locations of subplots within strips were established following hemp germination and initial development. Within each strip, plots (3 m long) of greatest uniformity were selected and randomized to N treatment. In 2020, N (46-0-0) was hand-applied between drill rows two weeks after seeding. A slow-release N source (34-0-0) was applied with the same method in 2021, 2022, and 2023 as some leaves had nutrient burn symptoms in 2020.

In 2020 and 2021, a non-selective herbicide (Roundup (Glyphosate, 0.48 kg a.i./L) at 2.34 L/ha) was applied to kill all grass before seeding. However, hemp plantings faced weed pressure primarily from yellow nutsedge (*Cyperus esculentus*), along with some pigweeds (*Amaranthus* spp.) and bindweed (*Convolvulus arvensis*). These were pulled or cut with hand tools to suppress weed pressure. The wider row spacing allowed for these practices to be implemented effectively.

In 2022 and 2023, fields were tilled before seeding. Because of unfavorable weather conditions (i.e., high wind), herbicide application was not possible at seeding. Weed pressure, primarily from pigweed and foxtail (*Setaria viridis*), was more significant after the emergence of hemp plants. Post-emergence herbicides (Moxy (Octanoic acid ester of bromoxynil* (3,5-dibromo-4-hydroxybenzonitrile) at 1.4 L/ha) (Winfield Solutions, LLC, Winthrop, MN, USA) and Poast (2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cycloxexen-1-one at 1.4 L/ha) (BASF) were applied 20 days after seeding.

2.5. Plant Measures

Plant heights were measured before harvests, which occurred when bracts at the bottom of the inflorescences began opening, revealing mature seeds. Whole plants were harvested from within a 0.25 m^2 quadrate placed randomly at three locations within each plot (0.75 m^2 total area sampled). Hemp plants were harvested on 10 September 2020, 23 July 2021, 24 July 2022, and 8 September 2023. Harvesting was delayed in 2023 as NWG 2463 and NWG 4113 are later-maturing cultivars. Total biomass yield and seed yield were measured after drying the collected samples and separating the seeds, respectively. Seed separation was completed using a homemade vacuum separator.

2.6. Statistical Analysis

Data were analyzed with ANOVA using Proc Mixed procedures of SAS Studio (version 3.8, Cary, NC, USA). The model tested the effects of cultivar and N fertility rates on plant heights. The year was included in the initial model but given significant ($p < 0.05$) year × N rate interactions, data were analyzed by year. N fertility rates and cultivars were considered fixed effects, while replication was considered a random effect. LS means and Tukey's adjusted differences were calculated. Results were considered statistically significant at $p < 0.05$ and considered trends when $0.05 < p \leq 0.10$.

ANOVA with polynomial contrast (e.g., linear, quadratic, cubic, quartic) was employed to investigate the impact of nitrogen (N) rates on seed yield and biomass yield. This analysis utilized the Proc GLM procedures in SAS Studio. Subsequently, regression analysis was conducted in Python, specifically utilizing the scipy stats model's library on the Google Colab platform. The determination of significant polynomial factors for seed yield and biomass yield was made, followed by data visualization using matplotlib.pyplot (version 3.7.1).

3. Results and Discussion

3.1. Weather Data

Growing season averages and totals are provided in Table 1 with distribution patterns in Figure 1. In general, precipitation was limited in 2022 compared to 2020, 2021, and 2023 at Blacksburg, VA, USA.

Table 1. Average mean, maximum and minimum temperatures, and total precipitation for the 2020–2023 growing seasons in Blacksburg, VA, USA.

Year	Season	Seasonal Temperature (°C)			Seasonal Precipitation (mm)
		Mean	Max	Min	Total
2020	19 June–10 September	23.3	29.0	17.5	524
2021	13 May–23 July	20.8	27.2	14.4	82
2022	17 May–24 July	22.1	29.0	15.1	75
2023	26 May–8 September	21.3	27.6	15.0	420

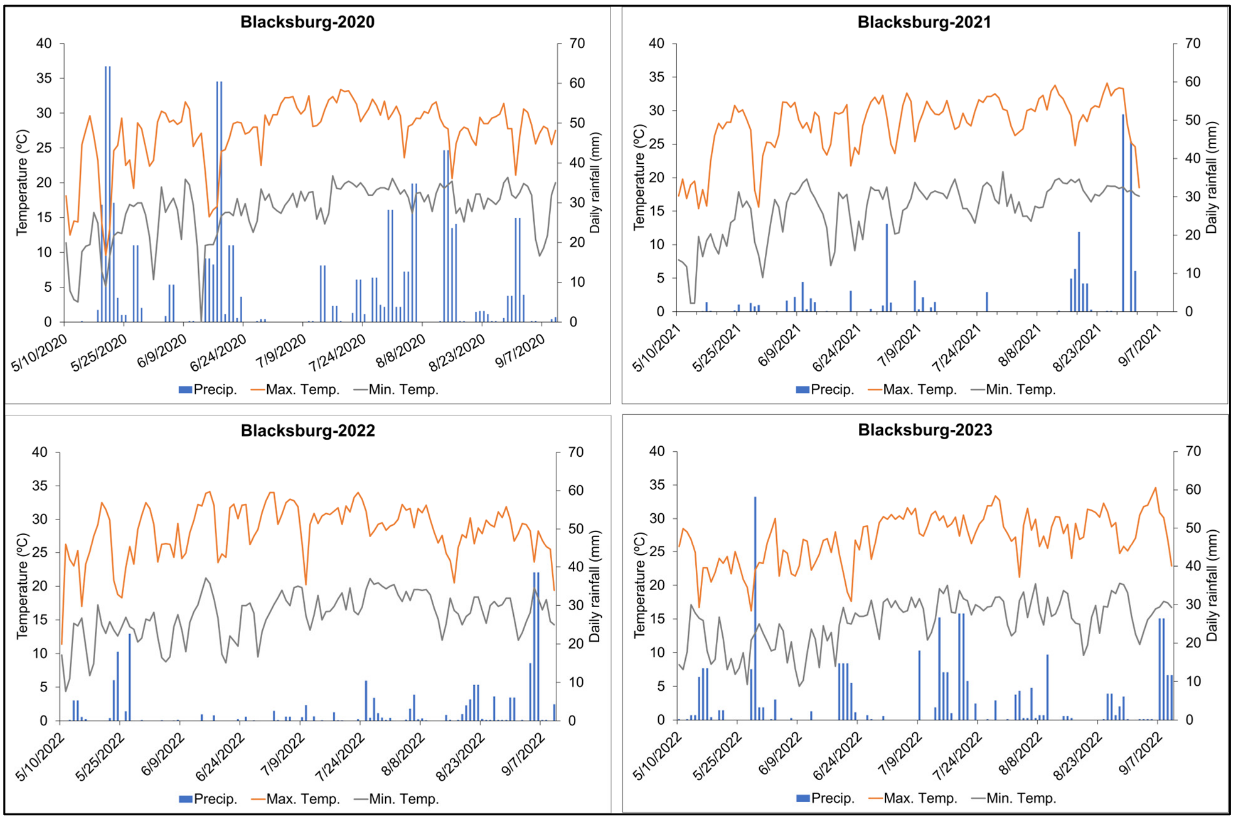

Figure 1. Daily maximum and minimum temperatures and precipitation for the hemp production study in Blacksburg, VA, USA, during the 2020–2023 growing seasons.

Although total precipitation differed little between 2021 and 2022, the distribution of precipitation varied substantially. In 2021, precipitation was distributed throughout the growing season, with rain events occurring soon after field establishment and during the vegetative growth stage. In 2022, precipitation occurred soon after seeding, which helped to establish the stand uniformly. Little precipitation occurred through the vegetative growth phase, followed by higher amounts of precipitation late in the growing season.

3.2. Plant Population

The plant population density varied across the years, although the seeding rate was the same. In 2020, the density was 35 plants per square meter, while in 2021, it was 17 plants per square meter. In 2022, a higher plant population density of 90 plants per square meter was maintained, and in 2023 it was 44 plants per square meter. These differences likely reflect the combination of seed quality, row spacing, and planting conditions in the early phase of establishment.

3.3. Plant Height

As expected, Joey, the dual-purpose cultivar, was taller ($p < 0.0001$) than Grandi in 2020, 2021, and 2023. Plant height exhibited no response to nitrogen fertility in 2020, likely influenced by late seeding. Hemp growth is regulated in relationship to day length [14], and initiation of the reproductive phase and of inflorescence development soon after planting limited Grandi's opportunity for vertical vegetative growth. This effect is particularly notable due to the cultivation of a photoperiod-sensitive cultivar originating from northern latitudes grown in a southern location [2]. A similar pattern of response occurred again in 2022, but in this case likely reflects that crop growth was limited by low seasonal precipitation with irregular temporal distribution. While precipitation occurred during the period of emergence and later in the growing season, hemp plants encountered reduced precipitation, particularly during the early vegetative phase (Figure 1). Height response to N was positive but moderate for cultivar Joey only in 2021; a stronger linear ($p < 0.0001$) response was observed in 2023 for the NWG 2463 and NWG 4113 cultivars. When N-rate effects were significant (2021 and 2023), plant heights differed little among N rates of 120 kg/ha or greater (Figure 2). Shorter plants in 2022 reflect the combination of limited rainfall, high-density plants, and high weed pressure during the growing season (Figure 1).

3.4. Biomass Yield

In 2020, both cultivars had a quadratic ($p = 0.0044$) yield response to N fertilizer, although the model fit was limited ($R^2 = 0.33$). Biomass yield was greater with the first N fertilizer increment applied (60 kg N ha^{-1}), but increasing application rates did not increase yield. Applying 240 kg N ha^{-1} produced an intermediate yield, suggesting a detrimental effect of high N to hemp growth. This likely reflects the negative effect of fertilizer burn with urea at the high N rate.

In 2021, response to N was linear ($p < 0.0001$) for both cultivars, and biomass yield increased incrementally with increasing N rate. Yield increases were about 11 and 26 kg of hemp biomass per kg N applied for Grandi and Joey, respectively. This difference in response reflects the greater biomass potential of dual-purpose cultivars such as Joey. The greatest average biomass yield for Grandi (5.2 Mg ha^{-1}) and Joey (9.9 Mg ha^{-1}) was in response to 240 kg N ha^{-1}. Joey demonstrated a stronger correlation with nitrogen inputs in producing biomass than Grandi.

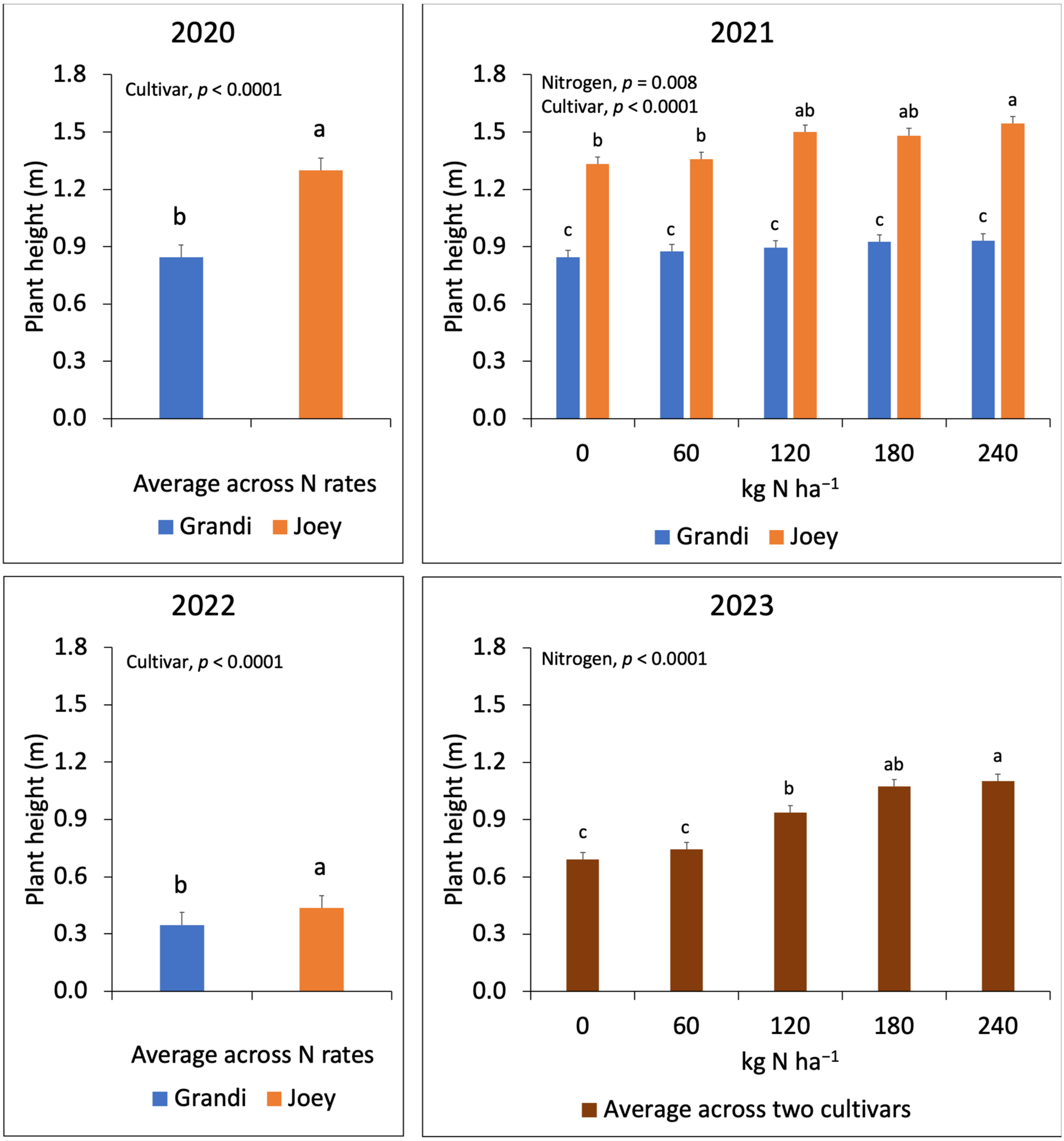

Figure 2. Mean plant height at harvest time under different rates of N fertilizer application for four different cultivars at Virginia Tech's Urban Horticulture Center (2020 and 2021) and Kentland Farm (2022 and 2023) in Blacksburg, VA. Different lowercase letters indicate significant differences at the 95% confidence level.

In 2022, the response to N was again linear (p = 0.0214) for both cultivars, although the model fit was quite weak (Figure 3). Biomass yield was compromised by limited rainfall, high plant populations, and particularly by weed pressure. High plant density resulted in lower biomass per plant due to reduced branching and slender stems, attributable to increased competition for resources among the plants. The highest biomass yield for Grandi (3.5 Mg ha^{-1}) and for Joey (4.9 Mg ha^{-1}) was recorded in response to 180 kg N ha^{-1}.

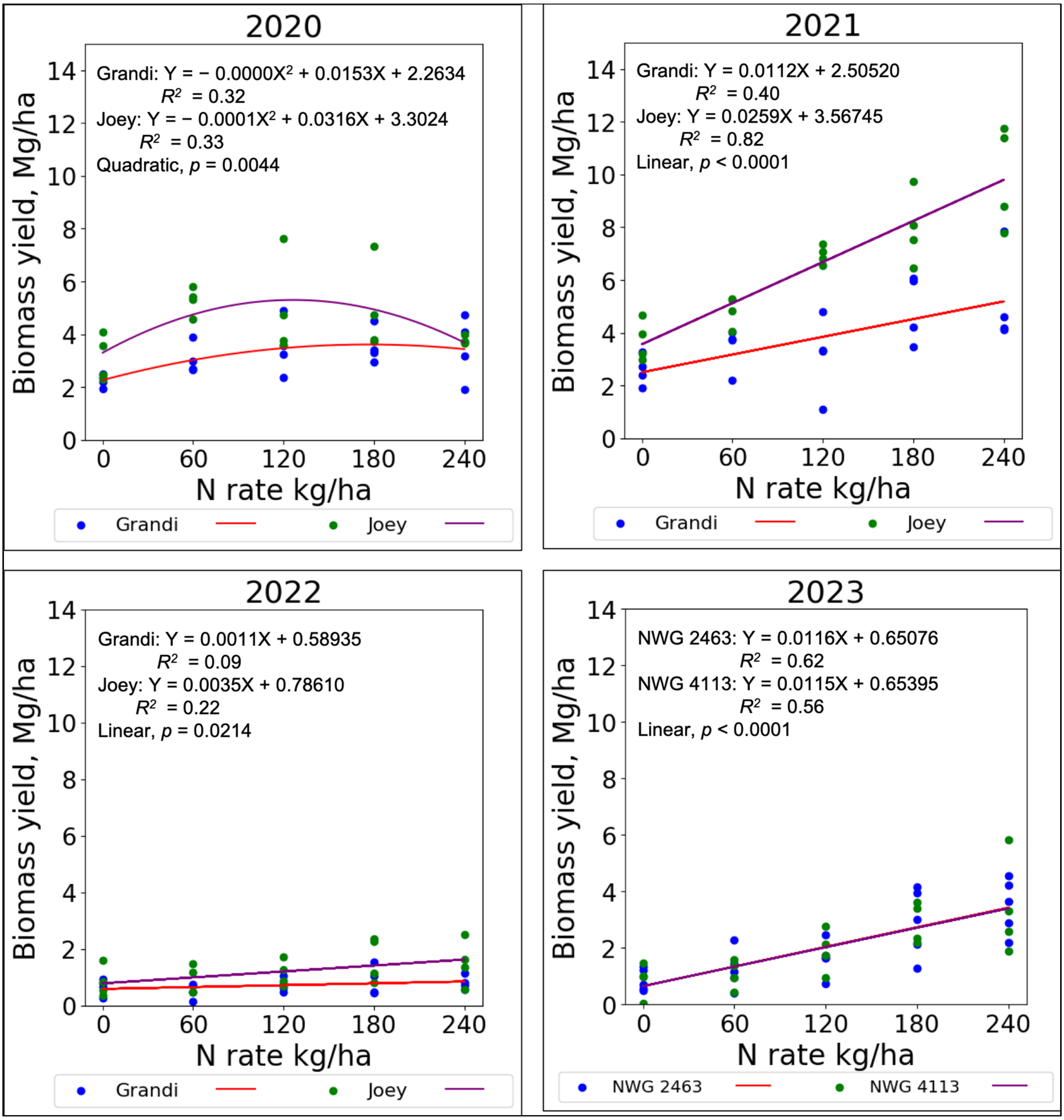

Figure 3. Regression analysis of biomass yield response to nitrogen rate for four hemp cultivars (Grandi and Joey in 2020, 2021, and 2022 and NWG 2463 and NWG 4113 in 2023) in Blacksburg, VA, USA.

Response to N in 2023 was linear ($p < 0.0001$) for both cultivars (Figure 3), with yield increases of about 11.5 kg hemp biomass per kg N applied. The greatest average biomass yield for NWG 2463 (3.51 Mg ha^{-1}) and NWG 4113 (3.41 Mg ha^{-1}) occurred with 240 kg N ha^{-1} application.

3.5. Seed Yield

In 2020, the seed yield of both Grandi and Joey responded quadratically ($p = 0.0113$) to N fertilizer, although these models were weakly fitted (low R^2). The mean seed yield increased with increasing N up to 120 kg ha^{-1} for Grandi (from 1025 to 1578 kg ha^{-1}), whereas for Joey, the response was only positive up to 60 kg N ha^{-1} (from 1050 to 1765 kg ha^{-1}). Within cultivars, seed yield did not increase with the addition of more N fertilizer. This limited response to N fertilizer indicates that other factors might have influenced yield that year. For instance, the late planting of these cultivars, developed in Canada, likely limited opportunities for vegetative growth (and limited response to N) before they started their reproductive growth phase. Moreover, the plants experienced some nutrient burn issues from the urea fertilizer, which was applied 2 weeks after planting. Fertilizer burn was more evident at the highest N fertility rates (180 and 240 kg N ha^{-1}) (Figure 4).

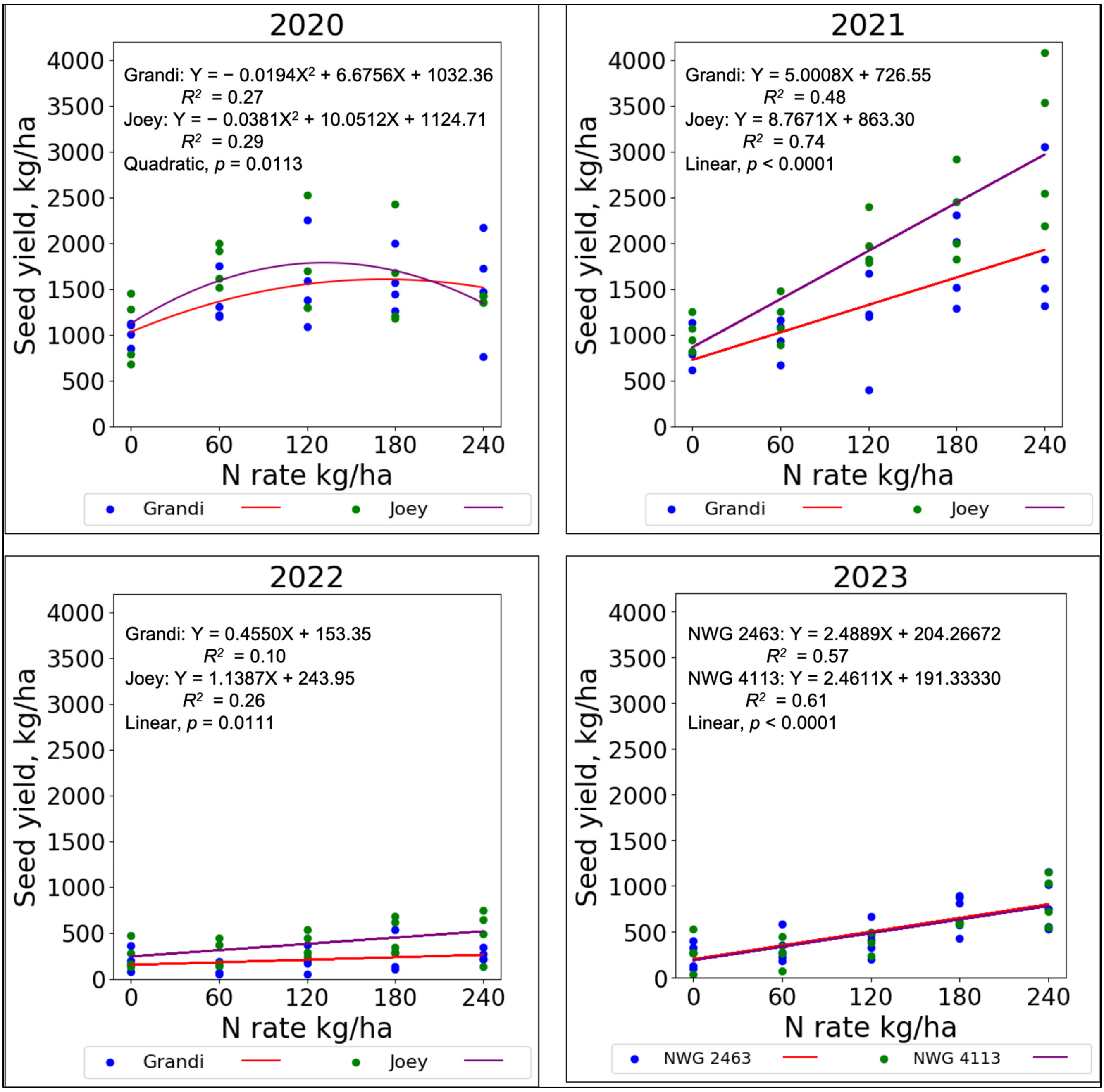

Figure 4. Regression analysis of seed yield response to nitrogen rate for four hemp cultivars (Grandi and Joey in 2020, 2021, and 2022 and NWG 2463 and NWG 4113 in 2023) in Blacksburg, VA, USA.

In 2021, the seed yield for Grandi and Joey increased linearly ($p < 0.0001$) with N fertilizer inputs, and a good fit ($R^2 = 0.74$) was seen for Joey. The mean seed yield for

Grandi increased from 837 with 0 N to 1927 kg ha^{-1} with 240 kg N ha^{-1}. The seed yield of Joey increased from 1020 with 0 N to 3087 kg ha^{-1} in response to 240 kg N ha^{-1} (Figure 4). Yield increases were about 5.0 and 8.8 kg hemp seed per kg N applied for Grandi and Joey, indicating both varieties have substantial potential responsiveness to fertility inputs. Overall, seed yield was higher in 2021. Lower plant density might be a contributing factor in producing greater seed yields, as low plant populations resulted in vigorous plants with lots of branching, which can produce a greater seed yield. However, the findings from Tang et al. [15] indicate that seed yield remained unaffected by variations in plant density ranging from 30 to 240 plants per square meter. In contrast, Campiglia et al. [10] reported an increase in seed yield with higher plant densities, specifically from 40 to 120 plants per square meter. Interestingly, in both studies, plants exhibited a trend towards slender growth as plant density increased.

In 2022, seed yield response to N was again linear (p = 0.0111) but weakly fitted for both cultivars, and coefficients of determination were low. Yield increases were around 0.5 and 1.1 kg of hemp seed per kg N applied for Grandi and Joey, respectively. The limited response to N inputs in 2022 was likely driven by the limited rainfall during the early vegetative stages in the 2022 growing season (Figure 1). This finding indicates the law of the minimum applies to hemp as well, as the plant could not respond to N inputs without sufficient water.

In 2023, NWG 2463 and NWG 4113 seed yield increased linearly ($p < 0.0001$) with N fertilizer inputs, and a similar response was observed for both cultivars (Figure 4). The overall seed yield was lower than in 2020 and 2021 because of high weed pressure. The mean seed yield increased from 265 to 831 kg ha^{-1} with the applied N rate of 0 to 240 kg N ha^{-1} (Figure 4). The yield increased by about 2.47 kg hemp seed per kg N applied, indicating responsiveness to fertility inputs despite significant weed pressure. Our data are generally consistent with those of Aubin et al. [9], who reported a positive and linear response to N at rates up to 200 kg/ha.

A positive response to N fertilization for biomass and seed yield was observed in all four years, although patterns of response differed by season. Hemp production was less than ideal in some seasons. When prophylactic application of systemic herbicide (glyphosate) at planting was not possible in 2022 and 2023, weed pressure was significant. Herbicide options to target grass and broadleaf weeds were limited, and those chemistries were ineffective at controlling the weed population in those seasons. Additionally, in 2022, hemp faced drought conditions after emergence due to limited precipitation. The combination of high plant density, weed pressure, and drought stress posed additional challenges for the hemp plants during the 2022 growing season. In 2023, foxtail surpassed hemp plants, particularly in plots with low fertility rates. In these plots, hemp plants exhibited shorter stature, were largely overshadowed by foxtail, and displayed reduced strength and vigor. Although hemp demonstrated significant potential for response to N fertility inputs, appropriate growing conditions and weed management are essential for success.

3.6. Correlation between Biomass Yield and Grain Yield

The correlation between biomass yield and grain yield was examined across multiple years for different hemp cultivars (Figure 5). In 2020, significant correlations were observed between hemp seed yields and biomass yields, with correlation coefficients of 0.99 for Grandi and 0.98 for Joey. Similarly, in 2021, strong correlations persisted, with coefficients of 0.96 for Grandi and 0.97 for Joey. However, in 2022, although still significant, correlations weakened slightly, with coefficients of 0.88 for Grandi and 0.97 for Joey. In 2023, different cultivars were examined, revealing correlations of 0.97 for NWG 2464 and 0.91 for NWG 4113 (Figure 5). These findings suggest a consistent relationship between biomass production and seed yield, indicating that cultivars with higher biomass yields tend to also produce higher seed yields. However, it should be noted that these results are specific to the grain-type hemp cultivars tested. Further investigation is warranted to assess the applicability of these findings to fiber-type cultivars.

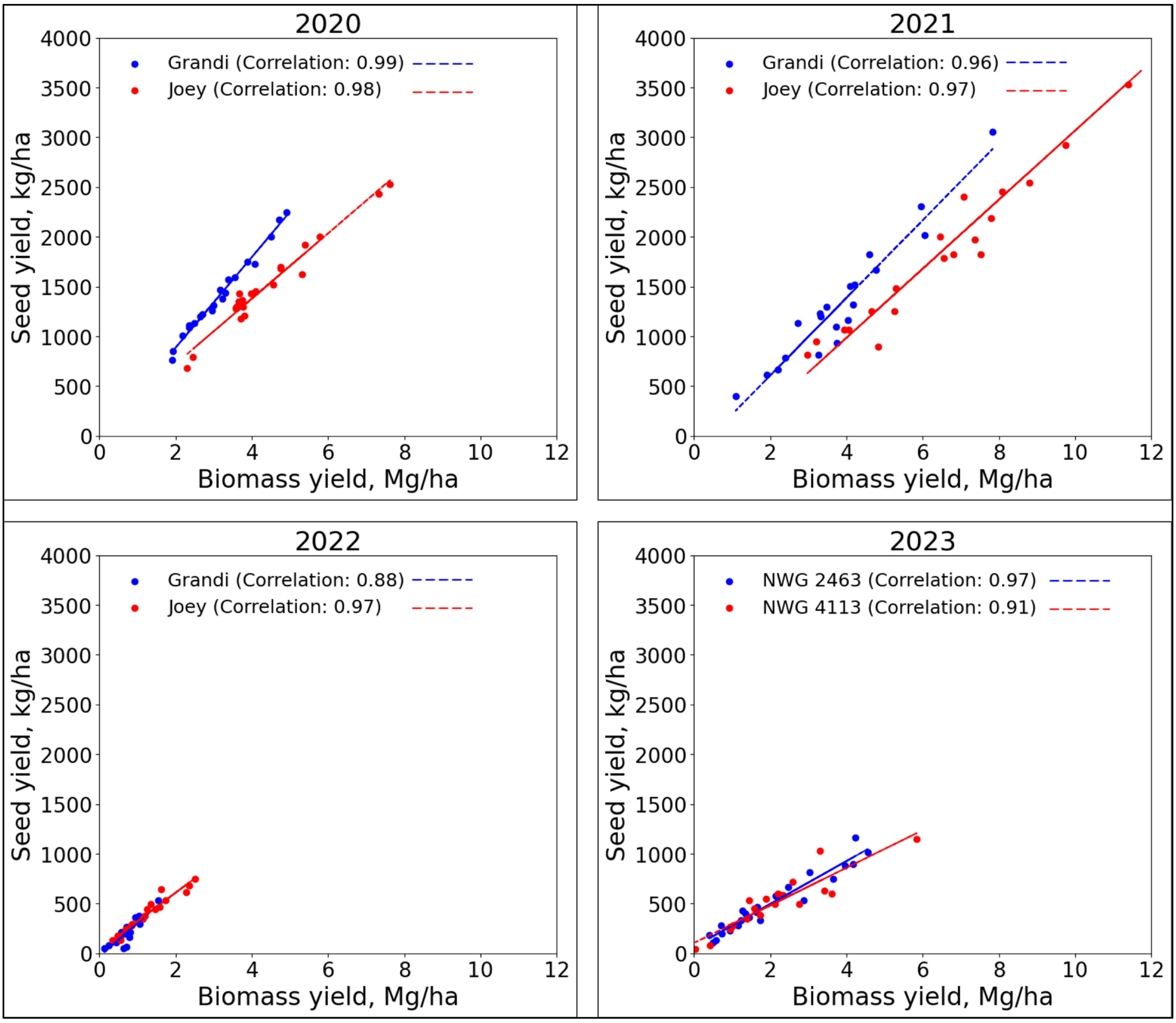

Figure 5. Correlation analysis between biomass yield and seed yield for four hemp cultivars (Grandi and Joey in 2020, 2021, and 2022 and NWG 2463 and NWG 4113 in 2023) in Blacksburg, VA, USA.

4. Conclusions

Nutrient management plays a critical role in establishing economically viable and sustainable cropping systems. Hemp seed yield was significantly but inconsistently influenced by N inputs, reflecting differences in establishment timing, precipitation, weed pressure, and competition from year to year. The results of this field study, which involved varying rates of nitrogen inputs and fluctuating weather and field conditions, contradict the common belief that hemp can be economically cultivated in agricultural settings with minimal or no inputs. In a year with a short growing season (2020), seed yields (1643 kg ha^{-1}) differed little among N rates greater than control. In 2021, with adequate rainfall and a full growing season (72 days), yield response to N was linear and reached 2510 kg ha^{-1} at the greatest N rate (240 kg N ha^{-1}). Limited rainfall and high competition (2022) produced only a weak response to N rate and low seed yields (382 kg ha^{-1}), with little difference among N rates. Even with adequate rainfall in 2023 (and a strong linear response to N), low seed yields (831 kg ha^{-1}) were observed at the greatest N rate of 240 kg N ha^{-1} due to high weed pressure. Similar patterns were observed for plant height and biomass response to fertility. These observations emphasize the influence that both abiotic and biotic factors have in determining hemp's response to the N rate. Future research should explore the interaction between N rates and other abiotic and biotic factors to develop more tailored recommendations for hemp cultivars specific to different physiographic regions.

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