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## Tools for Nitrogen Management of Wheat

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## Summary

*Various tools are available for nitrogen management of wheat. The purpose of this study was to determine how well these nitrogen management tools correlate with wheat yield. Studies were conducted at the University of Arizona Maricopa Agricultural Center in the 2019 growing seasons. Powell and Tiburon durum were grown with 8 nitrogen rates from 0 to 350 lb N/acre. The N management tools tested were: lower stem nitrate testing, Minolta chlorophyll meter, Greenseeker NDVI crop sensor, and the Cropscan multispectral radiometer. The following vegetation indices (VI) were calculated from the multispectral radiometer measurements: NDVI, Green NDVI, Red edge NDVI, Green VI, Difference VI, CI green, and CI Red edge. The optimum N rate in terms of yield quality was 250 lb N/acre. The correlation coefficients with yield averaged 0.25 (lower stem nitrate tissue test), 0.51-0.57 (chlorophyll meter), 0.72 (Greenseeker crop sensor), and 0.42-0.73 (vegetative indices). The vegetative indices we measured in this study show promise as tools for determining when and how much nitrogen fertilizer should be applied.*

## Introduction

Nitrogen is the main mineral nutrient required for wheat production in Arizona. Roughly half of the carbon footprint of a wheat crop is from the use of nitrogen fertilizer. Many growers in the Maricopa and Yuma areas have adopted the practice of not applying a preplant application of N fertilizer due to the high fertility status of the soils after vegetables or other input intensive crops. The preplant application of N fertilizer is not as efficient as later applications, so this represents a potential increase in efficiency. Phosphorus is sometimes required but is usually not needed after vegetable crops due to phosphorus fertilizer application to these crops.

Nitrogen fertilizer is normally applied to wheat either based on a predetermined recipe, visual appearance of the crop, or with a feedback approach such as tissue testing. Basing nitrogen fertilization on a predetermined recipe or the visual appearance of the crop may over- or under-estimate the crop need for nitrogen fertilizer compared with feedback approaches. The feedback approach that was originally developed in Maricopa and promoted by the University of Arizona is the lower stem nitrate test. The amount of nitrate in the lower stem at various growth stages has been correlated with the crop need for nitrogen fertilizer. However, the lower stem nitrate test is not instantaneous and the plant tissue must be dried and sent to a lab for analysis. Other tools for nitrogen management of wheat with a shorter time frame in the decision making are available such as the chlorophyll meter (eg. Minolta SPAD meter) and active optical sensors (eg. Greenseeker crop sensor) that measure reflectance of light and radiation from the crop canopy.

The lower stem nitrate test for wheat was developed by the University of Arizona and has been used effectively for decades. The chlorophyll meter is used by some crop consultants in Arizona, but the University of Arizona has not developed local guidelines for this instrument. Hand-held and tractor mounted active optical sensors have been tested for several years by the University of Arizona and USDA-ARS, but local guidelines have not been developed for these instruments yet.

## Procedure

Field trials were conducted at the University of Arizona Maricopa Agricultural Center where the accuracy of four nitrogen management tools were compared at multiple nitrogen rates. The durum varieties Powell and Tiburon were planted with a grain drill at a rate of 150 lbs seed/A. Nitrogen fertilizer in the form of urea (46-0-0) was applied at 8 rates from 0 to 350 lbs N/acre and split equally among five applications (Table 2). The experimental design was a split plot with two varieties as main plots and eight N rates as subplots and four replications. The subplot size was 20 ft wide x 20 ft long. The cultural practices are presented in Table 1.

The nitrogen management tools investigated in this study were lower stem nitrate (Ottman and Thompson, 2015), Minolta chlorophyll meter (SPAD 502), Greenseeker active-light handheld crop sensor, and a Cropscan passive multispectral radiometer with 16 wavelength bands (MSR 16). The wavelengths measured by multispectral radiometer included portions of the spectrum in the visible range and into the near-infrared. The filters were centered on the following peaks: 460, 510, 530, 550, 570, 590, 610, 630, 650, 670, 690, 720, 750, 780, 810, and 880nm. Measurements using these tools were taken on January 30, February 27, March 14, and March 27 in 2019. Lower stem nitrate content was determined by taking 20-40 lower stem samples, drying the samples, and analyzing for nitrate content. Chlorophyll meter measurements were taken from 5 measurements from 10 leaves and averaged. These measurements were taken from the most recent fully expanded leaf and the five leaves beneath this leaf. The Greenseeker handheld crop sensor was used by taking a single pass over each plot. The output from this sensor is NDVI, normalized difference vegetation index. Cropscan multispectral radiometer measurements were taken from three areas in the sensor FOV (field of view) over the plots then averaged. MSR-16 measurements were carried out in a two-hour span around solar noon to account for sun angle fluctuations. The following vegetation indices were calculated from the multispectral radiometer measurements: NDVI, Green NDVI, Red edge NDVI, Green VI, Difference VI, CI green, and CI Red edge (Table 3).

The following data was collected at harvest: grain yield, test weight, seed weight, plant height, lodging, grain protein, and HVAC. Due to extensive bird damage, the whole plots were not harvested but instead 1 meter of an undamaged row was selected for yield determination. Grain yields are expressed on an “as is” moisture basis. Test weight was calculated from the weight of 1 pint of grain. Seed weight was determined from 200 seed. HVAC was determined from 10 g of seed. Grain protein was determined from total N multiplied by 5.7 and expressed on a 12% moisture basis.

## Results and Discussion

Yield and other crop characteristics were very responsive to nitrogen fertilizer rate (Table 4). Yield increased with nitrogen rate up to about 250 lb N/acre after which yield decreased with increasing N rates. Test weight was not affected by N rate. Seed weight was lowest where no N fertilizer was applied and at the highest N rates. Plant height increased with N rate similar to the response of grain yield. Lodging occurred at N rates of 250 lb N/acre and higher. HVAC and grain protein increased with N rate. The durum crop responded to N fertilizer in a predictable and expected way. The optimum N rate was 250 lb N/acre in terms of yield.

The various nitrogen management tools tested in this study increased in their respective numeric values with N rate at all sampling times, locations, and varieties (Tables 5-9). The nitrogen management tools tested were lower stem nitrate, SPAD reading from the Minolta Chlorophyll Meter for the first through fifth fully expanded leaves, NDVI from the Greenseeker handheld crop sensor, and various calculated indices from readings obtained with the Cropscan MSR-16 multispectral radiometer.

Grain yield was correlated to the various nitrogen management tools tested in this study (Table 10). The correlation coefficient (r) with grain yield was 0.25 for stem nitrate and 0.51-0.57 for the SPAD readings on the first through fifth fully expanded leaves. However, the correlation coefficients for the spectral indices were generally higher and ranged from 0.42 to 0.73. NDVI measured using the Greenseeker Handheld Crop Sensor and the Cropscan MSR-16 multispectral radiometer averaged 0.72. The highest correlation coefficients were obtained from Red Edge NDVI (0.92) and Red Edge CI (0.91). The differences in correlation coefficients of yield vs the spectral indices may not be of practical significance except for Green VI, which had a much lower correlation coefficient (0.42) with yield than the other spectral indices (0.68-0.72).

In conclusion, the spectral indices we measured in this study show promise as tools for determining when and how much nitrogen fertilizer should be applied.

## Acknowledgments

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Table 1. Cultural practices for a wheat nitrogen management study in Maricopa, 2019.

| Cultural information | Maricopa |
|---|---|
| | |
| Previous crop | Fallow |
| Soil texture | Sandy loam |
| Planting date | 12/17/18 |
| Seeding rate | 150 lb/A |
| Irrigation dates | 12/18: 7.11 in<br>2/1: 5.10 in<br>3/1: 2.49 in<br>3/15: 3.42 in<br>3/29: 3.55 in<br>4/12: 4.56 in<br>4/26: 6.08 in<br>SUM = 32.3 in |
| Nitrogen application dates | 12/17, 1/30, 2/27, 3/14, 3/27 |
| Pesticides | None |

Table 2. Nitrogen fertilizer rates for a wheat nitrogen management study in Maricopa, 2019.

| Seasonal N rate | 12/17 Planting | 1/30 Tillering | 2/27 Jointing | 3/14 Boot | 3/27 Flowering |
|---|---|---|---|---|---|
| | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 |
| 50 | 10 | 10 | 10 | 10 | 10 |
| 100 | 20 | 20 | 20 | 20 | 20 |
| 150 | 30 | 30 | 30 | 30 | 30 |
| 200 | 40 | 40 | 40 | 40 | 40 |
| 250 | 50 | 50 | 50 | 50 | 50 |
| 300 | 60 | 60 | 60 | 60 | 60 |
| 350 | 70 | 70 | 70 | 70 | 70 |

Table 3. Vegetation indices calculated from the Cropscan multispectral radiometer and the algorithms used to do so in a wheat nitrogen management study in Maricopa, 2019.

| Vegetation index* | Algorithm (reflectance wavelength, nm) |
|---|---|
| | |
| NDVI | (690-810)/(690+810) |
| Green NDVI | (550-810)/(550+810) |
| Red edge NDVI | (720-750)/(720+750) |
| Green VI | (690-550)/(690+550) |
| Difference VI | 810-690 |
| CI green | (810/550)-1 |
| CI red edge | (750/720)-1 |

*NDVI = normalized difference vegetation index, VI = vegetation index, CI = chlorophyll index.

Table 4. Yield and plant and grain characteristics as affected by nitrogen rate for two varieties for a wheat nitrogen management study in Maricopa, 2019.

| Variety | N rate | Grain yield | Test weight | Seed weight | Plant height | Lodging | HVAC | Grain protein |
|---|---|---|---|---|---|---|---|---|
| | | lb/acre | lb/bu | mg | inches | % | % | % |
| | | | | | | | | |
| Powell | 0 | 2145 | 63.8 | 55.7 | 22 | 0 | 40 | 9.0 |
| | 50 | 4038 | 64.0 | 60.0 | 29 | 0 | 54 | 8.9 |
| | 100 | 4974 | 63.6 | 60.5 | 32 | 0 | 70 | 9.6 |
| | 150 | 6068 | 63.7 | 56.2 | 32 | 0 | 83 | 9.6 |
| | 200 | 4692 | 64.4 | 60.8 | 34 | 1 | 84 | 11.4 |
| | 250 | 6440 | 63.3 | 56.7 | 34 | 52 | 85 | 11.7 |
| | 300 | 4004 | 63.3 | 57.5 | 35 | 73 | 82 | 12.5 |
| | 350 | 5298 | 63.2 | 52.8 | 35 | 74 | 88 | 12.6 |
| Tiburon | 0 | 2389 | 62.0 | 53.2 | 22 | 0 | 19 | 9.1 |
| | 50 | 4822 | 62.3 | 66.7 | 28 | 0 | 27 | 8.8 |
| | 100 | 6432 | 62.7 | 59.0 | 32 | 0 | 37 | 9.4 |
| | 150 | 6747 | 63.3 | 66.0 | 35 | 0 | 58 | 10.2 |
| | 200 | 7991 | 63.1 | 69.7 | 35 | 0 | 78 | 10.7 |
| | 250 | 7745 | 62.9 | 69.8 | 36 | 1 | 91 | 12.6 |
| | 300 | 7223 | 62.6 | 60.7 | 36 | 13 | 94 | 13.3 |
| | 350 | 7479 | 62.1 | 58.3 | 33 | 19 | 93 | 13.0 |
| | | | | | | | | |
| Avg | 0 | 2267 | 62.8 | 54.4 | 22 | 0 | 30 | 9.0 |
| | 50 | 4430 | 63.1 | 63.3 | 29 | 0 | 41 | 8.9 |
| | 100 | 5703 | 63.1 | 59.8 | 32 | 0 | 53 | 9.5 |
| | 150 | 6408 | 63.4 | 61.1 | 33 | 0 | 71 | 9.9 |
| | 200 | 6342 | 63.6 | 65.3 | 34 | 0 | 81 | 11.1 |
| | 250 | 7092 | 63.0 | 63.3 | 35 | 26 | 88 | 12.2 |
| | 300 | 5614 | 62.8 | 59.1 | 35 | 43 | 88 | 12.9 |
| | 350 | 6388 | 62.5 | 55.6 | 34 | 47 | 90 | 12.8 |

Table 5. For 1/30 sampling date, lower stem nitrate, SPAD reading from the Minolta Chlorophyll Meter for the first through fifth fully expanded leaves, NDVI from the Greenseeker handheld crop sensor, and various calculated indices from readings obtained with the Cropscan MSR-16 multispectral radiometer as affected by nitrogen rate for two varieties for a wheat nitrogen management study in Maricopa, 2019.

| Variety | N rate (lb/a) | Stem $NO_3$ (ppm) | SPAD 1st leaf | SPAD 2nd leaf | SPAD 3rd leaf | SPAD 4th leaf | SPAD 5th leaf | NDVI Green-seeker | NDVI MSR-16 | Green NDVI | Red edge NDVI | Green VI | Differ-ence VI | Green CI | Red edge CI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | |
| Powell | 0 | 224 | 36.8 | 35.0 | 32.8 | . | . | 0.21 | 0.26 | 0.41 | 0.10 | 0.163 | 13.4 | 1.37 | 0.23 |
| | 50 | 1201 | 46.4 | 41.8 | 43.0 | . | . | 0.30 | 0.38 | 0.48 | 0.16 | 0.115 | 19.1 | 1.83 | 0.39 |
| | 100 | 2011 | 47.5 | 46.5 | 48.6 | . | . | 0.37 | 0.46 | 0.52 | 0.20 | 0.082 | 22.3 | 2.16 | 0.50 |
| | 150 | 2415 | 51.7 | 48.7 | 41.2 | . | . | 0.38 | 0.50 | 0.55 | 0.22 | 0.062 | 24.3 | 2.42 | 0.58 |
| | 200 | 3753 | 51.1 | 50.0 | 46.1 | . | . | 0.40 | 0.51 | 0.55 | 0.23 | 0.054 | 24.7 | 2.47 | 0.61 |
| | 250 | 4921 | 50.1 | 50.0 | 50.6 | . | . | 0.40 | 0.53 | 0.56 | 0.24 | 0.051 | 25.4 | 2.58 | 0.63 |
| | 300 | 4950 | 50.2 | 50.7 | 49.7 | . | . | 0.42 | 0.55 | 0.58 | 0.25 | 0.037 | 26.5 | 2.71 | 0.67 |
| | 350 | 5323 | 49.3 | 48.7 | 47.3 | . | . | 0.43 | 0.55 | 0.57 | 0.25 | 0.039 | 26.3 | 2.69 | 0.67 |
| Tiburon | 0 | 135 | . | . | . | . | . | 0.22 | 0.27 | 0.41 | 0.10 | 0.153 | 14.0 | 1.38 | 0.23 |
| | 50 | 363 | . | . | . | . | . | 0.29 | 0.38 | 0.47 | 0.16 | 0.115 | 18.8 | 1.78 | 0.37 |
| | 100 | 1412 | . | . | . | . | . | 0.35 | 0.48 | 0.53 | 0.21 | 0.074 | 23.3 | 2.30 | 0.54 |
| | 150 | 2602 | . | . | . | . | . | 0.37 | 0.48 | 0.55 | 0.20 | 0.093 | 23.5 | 2.45 | 0.52 |
| | 200 | 3506 | . | . | . | . | . | 0.39 | 0.53 | 0.57 | 0.24 | 0.045 | 25.7 | 2.60 | 0.64 |
| | 250 | 4344 | . | . | . | . | . | 0.40 | 0.56 | 0.58 | 0.25 | 0.033 | 26.8 | 2.74 | 0.68 |
| | 300 | 4111 | . | . | . | . | . | 0.40 | 0.57 | 0.59 | 0.26 | 0.030 | 27.1 | 2.83 | 0.70 |
| | 350 | 4925 | . | . | . | . | . | 0.42 | 0.59 | 0.60 | 0.27 | 0.015 | 28.0 | 2.95 | 0.74 |
| | | | | | | | | | | | | | | | |
| Avg | 0 | 180 | 36.8 | 35.0 | 32.8 | . | . | 0.22 | 0.26 | 0.41 | 0.10 | 0.158 | 13.7 | 1.38 | 0.23 |
| | 50 | 782 | 46.4 | 41.8 | 43.0 | . | . | 0.29 | 0.38 | 0.47 | 0.16 | 0.115 | 19.0 | 1.81 | 0.38 |
| | 100 | 1712 | 47.5 | 46.5 | 48.6 | . | . | 0.36 | 0.47 | 0.53 | 0.21 | 0.078 | 22.8 | 2.23 | 0.52 |
| | 150 | 2508 | 51.7 | 48.7 | 41.2 | . | . | 0.38 | 0.49 | 0.55 | 0.21 | 0.078 | 23.9 | 2.44 | 0.55 |
| | 200 | 3630 | 51.1 | 50.0 | 46.1 | . | . | 0.40 | 0.52 | 0.56 | 0.24 | 0.049 | 25.2 | 2.54 | 0.62 |
| | 250 | 4632 | 50.1 | 50.0 | 50.6 | . | . | 0.40 | 0.54 | 0.57 | 0.25 | 0.042 | 26.1 | 2.66 | 0.66 |
| | 300 | 4530 | 50.2 | 50.7 | 49.7 | . | . | 0.41 | 0.56 | 0.58 | 0.26 | 0.033 | 26.8 | 2.77 | 0.69 |
| | 350 | 5124 | 49.3 | 48.7 | 47.3 | . | . | 0.43 | 0.57 | 0.58 | 0.26 | 0.027 | 27.1 | 2.82 | 0.71 |

Table 6. For 2/27 sampling date, lower stem nitrate, SPAD reading from the Minolta Chlorophyll Meter for the first through fifth fully expanded leaves, NDVI from the Greenseeker handheld crop sensor, and various calculated indices from readings obtained with the Cropscan MSR-16 multispectral radiometer as affected by nitrogen rate for two varieties for a wheat nitrogen management study in Maricopa, 2019.

| Variety | N rate (lb/a) | Stem $NO_3$ (ppm) | SPAD 1st leaf | SPAD 2nd leaf | SPAD 3rd leaf | SPAD 4th leaf | SPAD 5th leaf | NDVI Green-seeker | NDVI MSR-16 | Green NDVI | Red edge NDVI | Green VI | Differ-ence VI | Green CI | Red edge CI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | |
| Powell | 0 | 37 | 36.9 | 34.3 | 28.7 | 25.3 | . | 0.30 | 0.22 | 0.49 | 0.04 | 0.306 | 13.1 | 2.00 | 0.08 |
| | 50 | 26 | 40.1 | 38.2 | 34.6 | 29.4 | . | 0.54 | 0.41 | 0.70 | 0.07 | 0.409 | 22.7 | 4.82 | 0.14 |
| | 100 | 35 | 43.9 | 40.9 | 35.1 | 30.4 | . | 0.68 | 0.53 | 0.79 | 0.09 | 0.459 | 30.3 | 7.85 | 0.19 |
| | 150 | 64 | 45.4 | 42.5 | 36.6 | 28.9 | . | 0.76 | 0.59 | 0.83 | 0.11 | 0.480 | 34.9 | 10.01 | 0.24 |
| | 200 | 162 | 45.7 | 43.4 | 36.2 | 32.0 | . | 0.80 | 0.62 | 0.85 | 0.12 | 0.488 | 37.7 | 11.57 | 0.27 |
| | 250 | 433 | 48.4 | 45.5 | 38.9 | 35.7 | . | 0.81 | 0.65 | 0.87 | 0.13 | 0.492 | 40.3 | 12.89 | 0.30 |
| | 300 | 896 | 49.3 | 45.4 | 40.4 | 34.7 | . | 0.83 | 0.66 | 0.87 | 0.13 | 0.490 | 40.6 | 13.06 | 0.31 |
| | 350 | 1305 | 48.9 | 48.4 | 42.7 | 38.4 | . | 0.85 | 0.67 | 0.87 | 0.14 | 0.495 | 42.0 | 13.76 | 0.33 |
| Tiburon | 0 | 39 | 33.6 | 32.6 | 28.3 | 22.8 | . | 0.34 | 0.23 | 0.51 | 0.04 | 0.317 | 14.1 | 2.20 | 0.08 |
| | 50 | 30 | 39.5 | 36.8 | 35.5 | 27.8 | . | 0.55 | 0.39 | 0.68 | 0.06 | 0.396 | 22.2 | 4.31 | 0.13 |
| | 100 | 59 | 42.3 | 41.1 | 38.4 | 32.5 | . | 0.72 | 0.51 | 0.79 | 0.08 | 0.458 | 30.6 | 7.43 | 0.18 |
| | 150 | 124 | 47.6 | 44.5 | 42.2 | 35.2 | . | 0.76 | 0.59 | 0.84 | 0.11 | 0.481 | 35.6 | 10.20 | 0.24 |
| | 200 | 144 | 47.4 | 46.0 | 43.1 | 39.1 | . | 0.81 | 0.62 | 0.85 | 0.12 | 0.491 | 38.5 | 11.62 | 0.27 |
| | 250 | 818 | 45.4 | 44.4 | 42.5 | 36.7 | . | 0.84 | 0.65 | 0.87 | 0.13 | 0.493 | 41.6 | 13.01 | 0.30 |
| | 300 | 825 | 49.2 | 47.6 | 45.7 | 42.1 | . | 0.85 | 0.66 | 0.87 | 0.14 | 0.498 | 43.2 | 13.76 | 0.32 |
| | 350 | 2052 | 47.9 | 48.5 | 46.3 | 41.5 | . | 0.86 | 0.67 | 0.87 | 0.14 | 0.493 | 44.5 | 13.85 | 0.33 |
| | | | | | | | | | | | | | | | |
| Avg | 0 | 38 | 35.2 | 33.4 | 28.5 | 24.0 | . | 0.32 | 0.23 | 0.50 | 0.04 | 0.312 | 13.6 | 2.10 | 0.08 |
| | 50 | 28 | 39.8 | 37.5 | 35.0 | 28.6 | . | 0.54 | 0.40 | 0.69 | 0.06 | 0.402 | 22.4 | 4.56 | 0.13 |
| | 100 | 47 | 43.1 | 41.0 | 36.8 | 31.4 | . | 0.70 | 0.52 | 0.79 | 0.09 | 0.458 | 30.5 | 7.64 | 0.19 |
| | 150 | 94 | 46.5 | 43.5 | 39.4 | 32.1 | . | 0.76 | 0.59 | 0.83 | 0.11 | 0.481 | 35.3 | 10.11 | 0.24 |
| | 200 | 153 | 46.5 | 44.7 | 39.7 | 35.6 | . | 0.80 | 0.62 | 0.85 | 0.12 | 0.490 | 38.1 | 11.59 | 0.27 |
| | 250 | 625 | 46.9 | 44.9 | 40.7 | 36.2 | . | 0.83 | 0.65 | 0.87 | 0.13 | 0.493 | 41.0 | 12.95 | 0.30 |
| | 300 | 861 | 49.2 | 46.5 | 43.0 | 38.4 | . | 0.84 | 0.66 | 0.87 | 0.14 | 0.494 | 41.9 | 13.41 | 0.31 |
| | 350 | 1679 | 48.4 | 48.5 | 44.5 | 40.0 | . | 0.85 | 0.67 | 0.87 | 0.14 | 0.494 | 43.3 | 13.81 | 0.33 |

Table 7. For 3/14 sampling date, lower stem nitrate, SPAD reading from the Minolta Chlorophyll Meter for the first through fifth fully expanded leaves, NDVI from the Greenseeker handheld crop sensor, and various calculated indices from readings obtained with the Cropscan MSR-16 multispectral radiometer as affected by nitrogen rate for two varieties for a wheat nitrogen management study in Maricopa, 2019.

| Variety | N rate (lb/a) | Stem $NO_3$ (ppm) | SPAD 1st leaf | SPAD 2nd leaf | SPAD 3rd leaf | SPAD 4th leaf | SPAD 5th leaf | NDVI Green-seeker | NDVI MSR-16 | Green NDVI | Red edge NDVI | Green VI | Differ-ence VI | Green CI | Red edge CI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | |
| Powell | 0 | 34 | 42.0 | 37.9 | 34.4 | 25.2 | 21.4 | 0.31 | 0.27 | 0.56 | 0.05 | 0.339 | 14.2 | 2.58 | 0.10 |
| | 50 | 18 | 47.1 | 44.2 | 42.1 | 33.9 | 28.9 | 0.55 | 0.46 | 0.75 | 0.08 | 0.434 | 24.4 | 6.05 | 0.18 |
| | 100 | 43 | 45.6 | 45.8 | 44.9 | 38.8 | 32.1 | 0.73 | 0.59 | 0.83 | 0.11 | 0.478 | 32.4 | 10.02 | 0.26 |
| | 150 | 67 | 49.7 | 50.1 | 49.1 | 39.1 | 32.9 | 0.79 | 0.63 | 0.85 | 0.13 | 0.484 | 36.8 | 11.62 | 0.30 |
| | 200 | 238 | 49.6 | 49.3 | 46.3 | 39.1 | 33.4 | 0.84 | 0.64 | 0.86 | 0.14 | 0.482 | 39.9 | 12.14 | 0.33 |
| | 250 | 731 | 50.7 | 51.8 | 49.1 | 40.7 | 34.8 | 0.86 | 0.65 | 0.86 | 0.15 | 0.479 | 42.3 | 12.21 | 0.34 |
| | 300 | 1232 | 51.9 | 51.7 | 48.4 | 38.8 | 30.6 | 0.87 | 0.65 | 0.86 | 0.15 | 0.479 | 43.1 | 12.38 | 0.35 |
| | 350 | 1433 | 50.1 | 50.6 | 49.5 | 41.8 | 32.9 | 0.88 | 0.65 | 0.86 | 0.15 | 0.475 | 44.1 | 12.06 | 0.35 |
| Tiburon | 0 | 21 | 41.2 | 37.1 | 32.5 | 24.1 | 20.6 | 0.34 | 0.29 | 0.58 | 0.05 | 0.353 | 15.7 | 2.90 | 0.11 |
| | 50 | 21 | 44.0 | 40.6 | 39.4 | 27.9 | 24.4 | 0.54 | 0.46 | 0.74 | 0.08 | 0.433 | 24.2 | 5.82 | 0.17 |
| | 100 | 46 | 46.5 | 46.8 | 45.6 | 37.2 | 29.8 | 0.71 | 0.57 | 0.82 | 0.11 | 0.479 | 31.8 | 9.28 | 0.24 |
| | 150 | 96 | 45.6 | 47.7 | 46.2 | 39.2 | 30.0 | 0.82 | 0.64 | 0.86 | 0.13 | 0.497 | 37.0 | 12.61 | 0.31 |
| | 200 | 200 | 49.3 | 50.2 | 48.7 | 40.3 | 31.2 | 0.84 | 0.65 | 0.87 | 0.14 | 0.500 | 39.8 | 13.35 | 0.34 |
| | 250 | 792 | 48.6 | 52.1 | 50.2 | 43.4 | 34.3 | 0.88 | 0.66 | 0.87 | 0.15 | 0.494 | 42.5 | 13.54 | 0.36 |
| | 300 | 1316 | 49.8 | 49.6 | 49.3 | 37.4 | 31.9 | 0.88 | 0.66 | 0.87 | 0.15 | 0.494 | 43.9 | 13.59 | 0.36 |
| | 350 | 2326 | 49.5 | 50.4 | 47.7 | 38.2 | 29.8 | 0.89 | 0.66 | 0.87 | 0.15 | 0.491 | 44.8 | 13.35 | 0.37 |
| | | | | | | | | | | | | | | | |
| Avg | 0 | 28 | 41.6 | 37.5 | 33.4 | 24.6 | 21.0 | 0.33 | 0.28 | 0.57 | 0.05 | 0.346 | 15.0 | 2.74 | 0.11 |
| | 50 | 20 | 45.5 | 42.4 | 40.8 | 30.9 | 26.6 | 0.54 | 0.46 | 0.74 | 0.08 | 0.434 | 24.3 | 5.93 | 0.18 |
| | 100 | 44 | 46.0 | 46.3 | 45.3 | 38.0 | 30.9 | 0.72 | 0.58 | 0.83 | 0.11 | 0.479 | 32.1 | 9.65 | 0.25 |
| | 150 | 81 | 47.6 | 48.9 | 47.6 | 39.1 | 31.4 | 0.80 | 0.63 | 0.86 | 0.13 | 0.491 | 36.9 | 12.11 | 0.31 |
| | 200 | 219 | 49.4 | 49.8 | 47.5 | 39.7 | 32.3 | 0.84 | 0.65 | 0.86 | 0.14 | 0.491 | 39.8 | 12.75 | 0.33 |
| | 250 | 761 | 49.6 | 51.9 | 49.6 | 42.1 | 34.5 | 0.87 | 0.65 | 0.87 | 0.15 | 0.486 | 42.4 | 12.88 | 0.35 |
| | 300 | 1274 | 50.9 | 50.6 | 48.8 | 38.1 | 31.2 | 0.88 | 0.66 | 0.87 | 0.15 | 0.486 | 43.5 | 12.98 | 0.36 |
| | 350 | 1879 | 49.8 | 50.5 | 48.6 | 40.0 | 31.4 | 0.89 | 0.65 | 0.86 | 0.15 | 0.483 | 44.5 | 12.70 | 0.36 |

Table 8. For 3/27 sampling date, lower stem nitrate, SPAD reading from the Minolta Chlorophyll Meter for the first through fifth fully expanded leaves, NDVI from the Greenseeker handheld crop sensor, and various calculated indices from readings obtained with the Cropscan MSR-16 multispectral radiometer as affected by nitrogen rate for two varieties for a wheat nitrogen management study in Maricopa, 2019.

| Variety | N rate (lb/a) | Stem $NO_3$ (ppm) | SPAD 1st leaf | SPAD 2nd leaf | SPAD 3rd leaf | SPAD 4th leaf | SPAD 5th leaf | NDVI Green-seeker | NDVI MSR-16 | Green NDVI | Red edge NDVI | Green VI | Differ-ence VI | Green CI | Red edge CI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | |
| Powell | 0 | 69 | 44.9 | 40.0 | 31.7 | 24.0 | 19.0 | 0.32 | 0.24 | 0.50 | 0.04 | 0.297 | 14.0 | 2.08 | 0.09 |
| | 50 | 39 | 51.3 | 48.3 | 38.5 | 32.3 | 29.2 | 0.53 | 0.44 | 0.71 | 0.08 | 0.389 | 24.1 | 5.03 | 0.18 |
| | 100 | 35 | 53.5 | 50.9 | 45.1 | 36.5 | 32.8 | 0.71 | 0.60 | 0.82 | 0.12 | 0.443 | 32.7 | 9.47 | 0.28 |
| | 150 | 150 | 54.1 | 52.5 | 45.2 | 40.2 | 31.5 | 0.78 | 0.67 | 0.87 | 0.15 | 0.469 | 38.2 | 13.26 | 0.36 |
| | 200 | 328 | 55.2 | 54.6 | 48.0 | 41.9 | 34.8 | 0.84 | 0.69 | 0.88 | 0.17 | 0.473 | 42.0 | 14.50 | 0.40 |
| | 250 | 510 | 55.6 | 54.8 | 46.9 | 43.3 | 41.4 | 0.86 | 0.70 | 0.88 | 0.17 | 0.474 | 44.8 | 14.81 | 0.41 |
| | 300 | 1867 | 55.1 | 55.3 | 49.0 | 44.0 | 37.8 | 0.86 | 0.70 | 0.88 | 0.17 | 0.470 | 45.4 | 14.83 | 0.42 |
| | 350 | 2851 | 55.3 | 56.8 | 49.2 | 44.6 | 40.9 | 0.87 | 0.70 | 0.88 | 0.17 | 0.474 | 46.9 | 14.78 | 0.42 |
| Tiburon | 0 | 51 | 41.0 | 34.8 | 26.8 | 19.7 | 21.8 | 0.33 | 0.26 | 0.52 | 0.05 | 0.307 | 14.8 | 2.27 | 0.10 |
| | 50 | 71 | 46.7 | 43.3 | 36.0 | 28.2 | 27.6 | 0.48 | 0.42 | 0.69 | 0.08 | 0.373 | 22.7 | 4.41 | 0.17 |
| | 100 | 36 | 46.1 | 45.9 | 41.7 | 35.1 | 29.2 | 0.66 | 0.57 | 0.80 | 0.11 | 0.441 | 31.3 | 8.42 | 0.26 |
| | 150 | 114 | 48.2 | 48.9 | 44.7 | 40.6 | 29.6 | 0.78 | 0.68 | 0.87 | 0.15 | 0.482 | 38.1 | 13.97 | 0.36 |
| | 200 | 166 | 51.6 | 52.1 | 47.9 | 43.4 | 35.2 | 0.81 | 0.70 | 0.89 | 0.17 | 0.490 | 41.4 | 15.79 | 0.40 |
| | 250 | 730 | 52.9 | 51.4 | 47.4 | 42.9 | 32.2 | 0.85 | 0.71 | 0.89 | 0.18 | 0.490 | 44.2 | 16.29 | 0.43 |
| | 300 | 1229 | 55.1 | 53.9 | 49.2 | 43.1 | 32.6 | 0.86 | 0.72 | 0.89 | 0.18 | 0.490 | 46.5 | 16.69 | 0.43 |
| | 350 | 2362 | 54.3 | 53.3 | 48.1 | 43.6 | 33.9 | 0.87 | 0.72 | 0.89 | 0.18 | 0.489 | 47.3 | 16.55 | 0.44 |
| | | | | | | | | | | | | | | | |
| Avg | 0 | 60 | 43.0 | 37.4 | 29.3 | 21.8 | 20.4 | 0.33 | 0.25 | 0.51 | 0.05 | 0.302 | 14.4 | 2.18 | 0.10 |
| | 50 | 55 | 49.0 | 45.5 | 37.3 | 30.2 | 28.4 | 0.51 | 0.43 | 0.70 | 0.08 | 0.381 | 23.4 | 4.72 | 0.18 |
| | 100 | 35 | 49.8 | 48.4 | 43.4 | 35.8 | 31.0 | 0.68 | 0.58 | 0.81 | 0.12 | 0.442 | 32.0 | 8.95 | 0.27 |
| | 150 | 132 | 51.2 | 50.7 | 45.0 | 40.4 | 30.5 | 0.78 | 0.68 | 0.87 | 0.15 | 0.476 | 38.1 | 13.62 | 0.36 |
| | 200 | 247 | 53.4 | 53.4 | 48.0 | 42.6 | 35.0 | 0.83 | 0.70 | 0.88 | 0.17 | 0.482 | 41.7 | 15.14 | 0.40 |
| | 250 | 620 | 54.3 | 53.1 | 47.2 | 43.1 | 36.8 | 0.85 | 0.71 | 0.89 | 0.17 | 0.482 | 44.5 | 15.55 | 0.42 |
| | 300 | 1548 | 55.1 | 54.6 | 49.1 | 43.6 | 35.2 | 0.86 | 0.71 | 0.89 | 0.18 | 0.480 | 46.0 | 15.76 | 0.43 |
| | 350 | 2606 | 54.8 | 55.0 | 48.6 | 44.1 | 37.4 | 0.87 | 0.71 | 0.89 | 0.18 | 0.481 | 47.1 | 15.66 | 0.43 |

Table 9. For the average of the sampling dates, lower stem nitrate, SPAD reading from the Minolta Chlorophyll Meter for the first through fifth fully expanded leaves, NDVI from the Greenseeker handheld crop sensor, and various calculated indices from readings obtained with the Cropscan MSR-16 multispectral radiometer as affected by nitrogen rate for two varieties for a wheat nitrogen management study in Maricopa, 2019.

| Variety | N rate (lb/a) | Stem $NO_3$ (ppm) | SPAD 1st leaf | SPAD 2nd leaf | SPAD 3rd leaf | SPAD 4th leaf | SPAD 5th leaf | NDVI Green-seeker | NDVI MSR-16 | Green NDVI | Red edge NDVI | Green VI | Differ-ence VI | Green CI | Red edge CI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | |
| Powell | 0 | 91 | 40.9 | 37.2 | 31.7 | 24.8 | 20.2 | 0.29 | 0.25 | 0.49 | 0.06 | 0.276 | 13.7 | 2.00 | 0.12 |
| | 50 | 321 | 46.2 | 43.0 | 38.7 | 31.9 | 29.0 | 0.48 | 0.43 | 0.66 | 0.10 | 0.337 | 22.6 | 4.43 | 0.22 |
| | 100 | 531 | 47.6 | 45.9 | 42.2 | 35.2 | 32.4 | 0.62 | 0.54 | 0.74 | 0.13 | 0.365 | 29.4 | 7.37 | 0.31 |
| | 150 | 674 | 49.9 | 48.4 | 43.4 | 36.0 | 32.2 | 0.68 | 0.60 | 0.78 | 0.15 | 0.374 | 33.6 | 9.33 | 0.37 |
| | 200 | 1120 | 50.2 | 49.2 | 43.7 | 37.6 | 34.1 | 0.72 | 0.62 | 0.79 | 0.16 | 0.374 | 36.1 | 10.17 | 0.40 |
| | 250 | 1649 | 51.5 | 50.6 | 45.4 | 39.9 | 38.1 | 0.73 | 0.63 | 0.79 | 0.17 | 0.374 | 38.2 | 10.62 | 0.42 |
| | 300 | 2236 | 52.0 | 50.8 | 46.2 | 39.2 | 34.2 | 0.75 | 0.64 | 0.80 | 0.18 | 0.369 | 38.9 | 10.74 | 0.44 |
| | 350 | 2728 | 51.3 | 51.7 | 47.1 | 41.6 | 36.9 | 0.76 | 0.64 | 0.80 | 0.18 | 0.371 | 39.8 | 10.82 | 0.44 |
| Tiburon | 0 | 62 | 38.6 | 34.8 | 29.2 | 22.2 | 21.2 | 0.31 | 0.26 | 0.50 | 0.06 | 0.283 | 14.7 | 2.19 | 0.13 |
| | 50 | 121 | 43.4 | 40.2 | 37.0 | 28.0 | 26.0 | 0.47 | 0.41 | 0.64 | 0.09 | 0.329 | 22.0 | 4.08 | 0.21 |
| | 100 | 388 | 44.9 | 44.6 | 41.9 | 34.9 | 29.5 | 0.61 | 0.53 | 0.74 | 0.13 | 0.363 | 29.2 | 6.86 | 0.30 |
| | 150 | 734 | 47.1 | 47.1 | 44.4 | 38.3 | 29.8 | 0.68 | 0.60 | 0.78 | 0.15 | 0.388 | 33.6 | 9.81 | 0.36 |
| | 200 | 1004 | 49.4 | 49.4 | 46.6 | 40.9 | 33.2 | 0.71 | 0.63 | 0.79 | 0.17 | 0.381 | 36.4 | 10.84 | 0.41 |
| | 250 | 1671 | 49.0 | 49.3 | 46.7 | 41.0 | 33.2 | 0.74 | 0.65 | 0.80 | 0.18 | 0.377 | 38.8 | 11.40 | 0.44 |
| | 300 | 1870 | 51.3 | 50.3 | 48.1 | 40.8 | 32.2 | 0.75 | 0.65 | 0.81 | 0.18 | 0.378 | 40.2 | 11.72 | 0.45 |
| | 350 | 2916 | 50.6 | 50.7 | 47.3 | 41.1 | 31.9 | 0.76 | 0.66 | 0.81 | 0.19 | 0.372 | 41.2 | 11.67 | 0.47 |
| | | | | | | | | | | | | | | | |
| Avg | 0 | 76 | 39.8 | 36.0 | 30.5 | 23.5 | 20.7 | 0.30 | 0.25 | 0.50 | 0.06 | 0.279 | 14.2 | 2.10 | 0.13 |
| | 50 | 221 | 44.8 | 41.6 | 37.9 | 29.9 | 27.5 | 0.47 | 0.42 | 0.65 | 0.10 | 0.333 | 22.3 | 4.26 | 0.22 |
| | 100 | 459 | 46.3 | 45.3 | 42.1 | 35.1 | 31.0 | 0.61 | 0.54 | 0.74 | 0.13 | 0.364 | 29.3 | 7.12 | 0.31 |
| | 150 | 704 | 48.6 | 47.7 | 43.9 | 37.2 | 31.0 | 0.68 | 0.60 | 0.78 | 0.15 | 0.381 | 33.6 | 9.57 | 0.36 |
| | 200 | 1062 | 49.8 | 49.3 | 45.1 | 39.3 | 33.6 | 0.72 | 0.62 | 0.79 | 0.17 | 0.378 | 36.2 | 10.50 | 0.40 |
| | 250 | 1660 | 50.3 | 50.0 | 46.0 | 40.5 | 35.7 | 0.74 | 0.64 | 0.80 | 0.18 | 0.376 | 38.5 | 11.01 | 0.43 |
| | 300 | 2053 | 51.7 | 50.6 | 47.1 | 40.0 | 33.2 | 0.75 | 0.65 | 0.80 | 0.18 | 0.373 | 39.5 | 11.23 | 0.45 |
| | 350 | 2822 | 50.9 | 51.2 | 47.2 | 41.3 | 34.4 | 0.76 | 0.65 | 0.80 | 0.18 | 0.371 | 40.5 | 11.25 | 0.45 |

Table 10. Correlation coefficient for grain yield vs lower stem nitrate, SPAD reading from the Minolta Chlorophyll Meter for the first through fifth fully expanded leaves, NDVI from the Greenseeker handheld crop sensor, and various calculated indices from readings obtained with the Cropscan MSR-16 multispectral radiometer as affected by nitrogen rate for two varieties for a wheat nitrogen management study in Maricopa, 2019.

| Date | Variety | Stem $NO_3$ (ppm) | SPAD 1st leaf | SPAD 2nd leaf | SPAD 3rd leaf | SPAD 4th leaf | SPAD 5th leaf | NDVI Green-seeker | NDVI MSR-16 | Green NDVI | Red edge NDVI | Green VI | Differ-ence VI | Green CI | Red edge CI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | |
| 1/30 | Powell | 0.31 | . | . | . | . | . | 0.58 | 0.53 | 0.53 | 0.52 | -0.52 | 0.53 | 0.51 | 0.51 |
| | Tiburon | 0.82 | . | . | . | . | . | 0.78 | 0.77 | 0.87 | 0.69 | -0.55 | 0.79 | 0.84 | 0.70 |
| | Avg | 0.56 | . | . | . | . | . | 0.68 | 0.65 | 0.70 | 0.60 | -0.54 | 0.66 | 0.68 | 0.61 |
| | | | | | | | | | | | | | | | |
| 2/27 | Powell | 0.02 | 0.32 | 0.25 | 0.12 | -0.01 | . | 0.60 | 0.55 | 0.57 | 0.52 | 0.56 | 0.55 | 0.51 | 0.52 |
| | Tiburon | 0.36 | 0.83 | 0.81 | 0.77 | 0.80 | . | 0.90 | 0.91 | 0.92 | 0.86 | 0.92 | 0.88 | 0.86 | 0.84 |
| | Avg | 0.19 | 0.57 | 0.53 | 0.44 | 0.39 | . | 0.75 | 0.73 | 0.74 | 0.69 | 0.74 | 0.72 | 0.69 | 0.68 |
| | | | | | | | | | | | | | | | |
| 3/14 | Powell | -0.13 | 0.27 | 0.32 | 0.56 | 0.28 | 0.18 | 0.58 | 0.57 | 0.57 | 0.56 | 0.57 | 0.54 | 0.55 | 0.56 |
| | Tiburon | 0.43 | 0.77 | 0.87 | 0.87 | 0.77 | 0.55 | 0.90 | 0.92 | 0.92 | 0.90 | 0.92 | 0.89 | 0.91 | 0.89 |
| | Avg | 0.15 | 0.52 | 0.59 | 0.71 | 0.52 | 0.37 | 0.74 | 0.75 | 0.74 | 0.73 | 0.74 | 0.71 | 0.73 | 0.72 |
| | | | | | | | | | | | | | | | |
| 3/27 | Powell | -0.10 | 0.38 | 0.28 | 0.21 | 0.29 | 0.28 | 0.55 | 0.56 | 0.57 | 0.53 | 0.57 | 0.53 | 0.54 | 0.53 |
| | Tiburon | 0.29 | 0.73 | 0.86 | 0.92 | 0.91 | 0.70 | 0.90 | 0.92 | 0.92 | 0.89 | 0.92 | 0.87 | 0.86 | 0.88 |
| | Avg | 0.10 | 0.56 | 0.57 | 0.56 | 0.60 | 0.49 | 0.73 | 0.74 | 0.75 | 0.71 | 0.75 | 0.70 | 0.70 | 0.70 |
| | | | | | | | | | | | | | | | |
| Avg | Powell | 0.03 | 0.32 | 0.28 | 0.29 | 0.19 | 0.23 | 0.58 | 0.55 | 0.56 | 0.54 | 0.30 | 0.54 | 0.53 | 0.53 |
| | Tiburon | 0.47 | 0.78 | 0.85 | 0.85 | 0.83 | 0.63 | 0.87 | 0.88 | 0.91 | 0.83 | 0.55 | 0.86 | 0.87 | 0.83 |
| | Avg | 0.25 | 0.55 | 0.56 | 0.57 | 0.51 | 0.43 | 0.72 | 0.72 | 0.73 | 0.68 | 0.42 | 0.70 | 0.70 | 0.68 |