Hyperspectral Remote Sensing of Potato Plant Nutrient Deprivation and Vegetation Stress using High-Resolution Spectroradiometry for Minimal Input Agricultural Systems

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Abstract

Nitrogen is a plant growth limiting nutrient in natural ecosystems, however, many agricultural systems are saturated due to high fertilizer applications. This can lead to higher costs, nitrogen leakage into the environment and unnecessary GHG emissions that contribute to climate change. To avoid this, Neilson (2021) has proposed an approach based on minimal input agricultural systems (MIAS). MIAS seeks to grow crops with limited fertilizer inputs. This is accomplished through targeted/precision fertilizer placement, managing plant physiology to operate at higher efficiencies and adopting new varieties. To work optimally MIAS requires methods to quickly assess plant nutrient status and adjust fertilizer applications accordingly. This study tested remote sensing for detecting stress in potato plants, based on two separate and independent laboratory remote sensing experiments. The goal is to determine minimal input levels applied to a starvation agricultural system that provide yields equivalent (or perhaps even improving upon) those obtained using current excessive inputs, both in terms of yield and, importantly, quality. This research is at the front-end of a proposed paradigm shifting new approach to agriculture. We are being careful to start at first principles in this work; thus the study presented here is based on multiple trials and independent tests. Results testing experimental approaches and N deprivation assessment determined the optimal leaf density and timing of measurements and demonstrated a capability to detect vegetation stress and N deprivation in three potato varieties. These results will inform next steps for future RPAS/UAV/airborne/satellite studies and be used to develop other plant physiology assessment methods.

1. Introduction

Minimal input agricultural systems (MIAS) as proposed in our earlier work by Neilson (2021) represent an innovative new way for agriculture that optimizes management inputs for improved food production. Rather than operating on the principle of providing excess nutrients to alleviate limitations on growth, MIAS seeks to alter plant physiology through initial starvation and micro-dosing fertilizer such that higher plant growth rates can be achieved at lower nutrient levels. The benefits of such a system are lower nutrient inputs (less cost) and less nutrient leakage/waste. This would reduce environmental impacts of agriculture and lower climate change inducing GHG emissions. Further, the MIAS approach represents a fundamental shift away from systems that emphasize N use efficiency within an unlimited input framework (Nyiraneza et al. 2021). Our focus in this study is potato crops, however, the MIAS approach is applicable to most any agricultural crop and setting.

For MIAS to be feasible it requires methods to assess plant nutrient and physiological/stress status and then use this information to adjust fertilizer application (Figure 1). It also necessitates the collection of datasets to generate nutrient status models which can be ground-truthed. In terms of this next paper, and drawing on the international remote sensing expertise assembled for this team for this next phase agricultural work, we identify remote sensing as having a key role in MIAS at two fundamental levels. We are testing this for remote sensing of: (i) plant characteristics as expressed in above-ground potato leaves, and (ii) french fries and potato chip characteristics from harvested potato tubers. Our multi-year remote sensing research to date is addressing both of these levels (i.e. plant leaves and tubers), however, in this study we report on potato leaves only, and here we present the experimental design, methods and results from two separate, independent agricultural laboratory experiments. There are several related goals in both experiments, and accordingly, parts of the experimental design are similar. In those cases, the descriptions are not repeated and instead simply refer to the previous experiment in this paper. We then discuss and interpret the overall results from both experiments, and in the context of next steps in this work.

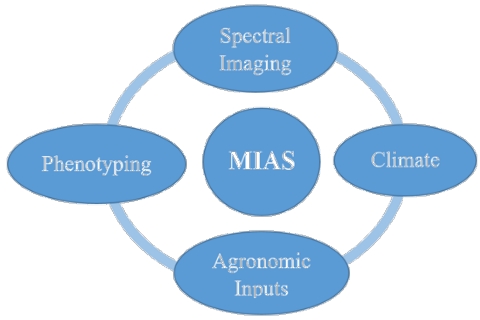

Figure 1: Minimal input agricultural systems (MIAS).

2. EXPERIMENT #1 – Methods and Initial Results

2.1 Experiment #1 – Agricultural Plant Preparation

The main tests pose the question: "Can remote sensing discriminate amongst potato plants subjected to different levels of vegetation stress and N fertilizer input?". The first set of experiments focused on vegetation stress from variable N treatments and involved one type of potato but at different plant stages and generations [Experiment #2 assesses different potato varieties]. For Experiment #1, vegetation condition was assessed using remote sensing spectroscopy which was needed to determine at what fertilizer input level do plants cease to be stressed (Nigon et al. 2015; Rady and Guyer, 2015). Potato plants were grown by Agriculture and Agri-Food Canada (AAFC) staff in a greenhouse, treated with varying levels of N, harvested at specified times in the growth cycle, and grouped by level of nitrogen input treatment. Potato plant petioles (stems) were removed, with terminal leaflets extracted for spectral measurement. All leaflet samples were bagged, labelled, and stored in ice-packed coolers for transport to the University of Lethbridge Alberta Terrestrial Imaging Centre (ATIC), now the Institute for Geospatial Inquiry, Instruction and Innovation (i4Geo) Labs. Samples remained bagged in the cooler except when being measured spectrally. The four sample groups of N levels were not disclosed to ATIC/i4Geo personnel and included replicates, with some of the samples harvested from different plant generations as part of the AAFC plant growth experimental design.

2.2 Experiment #1 – Remote Sensing Protocols

Using potato plant samples from AAFC, a laboratory spectral measurement experiment was designed and implemented at one of the ATIC/i4Geo Remote Sensing Labs at the University of Lethbridge. In a series of blind tests, AAFC potato plants were provided from 4 sample groups, with each group having a different level of nitrogen input varying from zero to double typical field applications. The remote sensing goal was to determine if we could detect different levels of plant stress, and what measurement conditions and protocols are required, including future operational considerations.

The highly controlled remote sensing laboratory setting at the ATIC/i4Geo Lab used an ASD FieldSpec3 full range spectroradiometer (wavelength [λ] range: 350-2500nm; nominal 1-3nm spectral resolution) with adjustable directional lighting in a controlled, dark environment. The measurement set-up (Figure 2) included a table with black covering, tripod-mounted fore-optic, and a Spectralon (PTFE) white reference panel for reflectance calibration. For all spectral measurements, a 30° illumination zenith angle and 5° field-of-view fore-optic were used, with nadir view angle and sensor height adjusted to obtain a 2.10 cm measurement diameter. This ensured the horizontal target surface area coverage for spectral measurement included plant material only. White reference panel measurements were obtained at the start and end of each group, with reflectance calculated with reference to panel calibration coefficients specific to the PTFE panel used. Thus the standard reflectance equation in the context of this protocol was:

$$\left(\frac{Dn}{WR} x\ Calibration\ Factor\right) = Reflec\tan c\,e$$

where target DN is the reflected energy sensed from the plant target expressed as an instrument specific digital number (DN), panel DN (in this case, a white reference panel, WR) is the reflected energy from the near coincident panel measurement to capture the incident irradiance, and calibration factor is the panel-specific, per wavelength % of energy reflected by the calibration panel throughout the instrument spectrum range. All spectral measurements were obtained after dark-current corrections and optimised to the illumination conditions present, which were constant.

Figure 2: Spectroradiometer measurement setup at ATIC/i4Geo, University of Lethbridge.

2.3 Experiment #1 – Three Sets of Remote Sensing Tests

Three sets of tests were performed in the ATIC/i4Geo RS Lab to assess: (i) optical thickness of leaf samples; (ii) sample measurement stability over time, and (iii) plant stress. The first two tests were required to perform the third reliably. In this section, we present the specific experimental lab protocols, and examples of the main results, initially only in terms of the primary outcomes necessary to inform the following test. Discussion and interpretation of specific test results are not provided in this section, as this is instead done in §4.0.

2.3.1 Experiment #1 – Test 1: Plant Optical Thickness: For test 1, plant arrangement in horizontal and vertical components as well as optical properties must be carefully considered to ensure proper target measurements as representative targets for all plant samples in this experiment (and also in Experiment #2, which involves comparisons amongst treatment types and potato varieties). This is also important in respect of follow-on field and in situ greenhouse spectral measurements for use and comparison with the laboratory spectra used here. In terms of horizontal placement, this is relatively straight-forward as a function of the measured target dimensions, and the surface-based field-of-view (FOV) as calculated from the instrument setup (sensor height and FOV angle). We were careful to ensure that the FOV diameter was always at most 50% of the minimum length dimension of the potato plant sample, to ensure no external interference from energy reflected from the background surface [other and adjacent incident energy sources were nil in the highly controlled, purpose-build remote sensing laboratory, including with respect to incident source irradiance].

In the vertical [plant] dimension, due to transmission of incident energy through leaves, multiple leaf layers are needed to ensure reflected energy is from plant material only (and not from background or other factors), thus achieving an optically thick stack. This approach also follows the conclusions and recommendations from our earlier field and airborne remote sensing work with potatoes that focused on deriving biophysical and structural plant information (Peddle and Smith, 2005) and which involved an extensive comparison of different methods.

A maximum of 15 leaf layers were tested. Results (Figure 3) indicated that a minimum of 3 stacked leaves are required, with a recommendation that five be used to ensure higher consistency across different sampling factors.

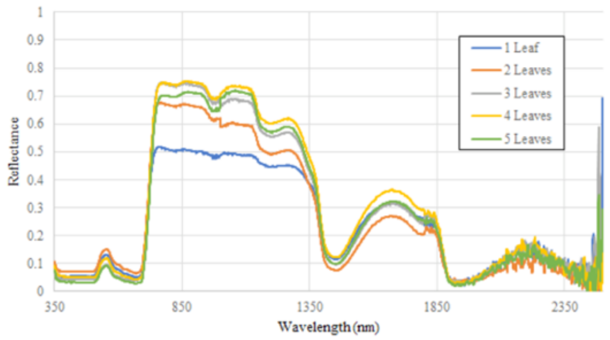

Figure 3: Reflectance spectra from different number of stacked leaf layers.

2.3.2 Experiment #1 –Test 2: Multi-Day Spectral Timing:

In Test 2, we consider measurement timing. This is important given that the plants were harvested and transported from AAFC to the ATIC/i4Geo RS lab for measurement. We need to ensure that the time after harvest does not influence spectral measurement, and further, with respect to longer-term objectives that will assess crops in field and greenhouse settings where similar harvesting will be applied. In this first test, we needed to consider a longer range of time intervals and thus we arranged for repeat measurements primarily at the scale of several days, although we did include an immediate set, and soon thereafter [+2hrs]. In total, Test 2 involved replicate spectral measurement of individual sample sets at different times ranging from T0 (spectral measurement as soon as samples were received at ATIC/i4Geo), to T+2hrs, T+24hrs, T+48hrs and T+64hrs. Results (Figure 4) indicated that reflectance spectra remain consistent within 24 hrs, possibly longer. As we did not assess more refined time windows within 24 hrs, we used the early window measurement protocols within the remainder of this Test set, and address this refinement in Experiment #2 (§3.3.2), noting however that this did not affect the results nor outcomes in this first Experiment.

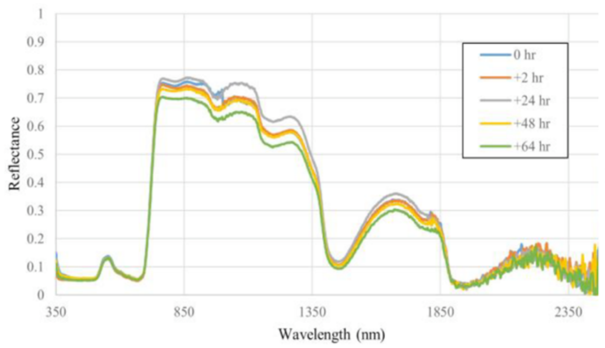

Figure 4: Reflectance spectra at different time points. Results from Sample A, using three leaf layers

2.3.3 Experiment #1 –Test 3: Potato Plant Stress:

For test 3, plant stress was discriminated across the 4 sample groups of variable nitrogen content (Figure 5). Based on outcomes from the first two tests, 3 leaf layers were measured at T+2hrs. Good discrimination was found across all 4 samples. Spectral profiles were generally consistent, with magnitude of reflectance driving the primary discrimination. This separation can reasonably be equated to different levels of plant stress, however, a more rigorous analysis would be required to quantify this further and relate that to minimal inputs.

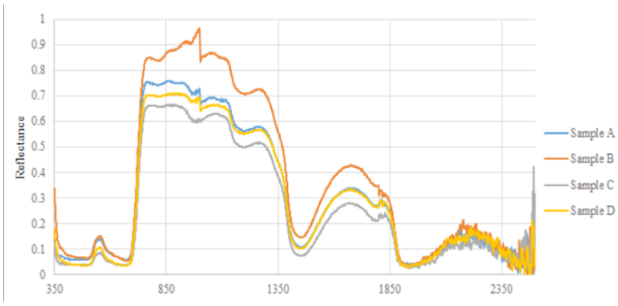

Figure 5: Reflectance spectra of plants with different levels of nitrogen input and stress.

Further discussion of the results from all three of these tests including specific wavelength recommendations, N treatments and agricultural implications are provided later in this paper (from §4.0), when we amalgamate the overall results from both experiments. One of the main outcomes from this Experiment #1 was rationale for performing additional tests to consider broader factors and more focused N testing, as done in Experiment #2, described next.

3. EXPERIMENT #2 – Methods and Initial Results

One of our main requirements in Experiment #2 was to further assess different types of potatoes, and with a specific focus on N deprivation. To test this, we designed a controlled growth and fertilization experiment, from which potato leaves were extracted and their spectral reflectance derived from hyperspectral data acquired with a spectroradiometer so that we can assess an extended spectrum and at high spectral resolution (350-2500nm). As with the plant growth and treatment, the remote sensing data acquisition was also obtained in a highly controlled laboratory setting. The results from this experiment will further inform our broader, multi-year laboratory studies and also planned future RPAS / airborne / satellite studies across different scales and fields.

3.1 Experiment #2 – Agricultural Plant Preparation

For the nutrient deprivation experiment for potato plants, experimental control was achieved for potatoes grown in an AAFC greenhouse (Figure 6). Potato plants were supplied with fertilizer in ten doses over a three-month period using a subsurface drip lines system. Three varieties were included (Ranger Russet, Russet Burbank, and Shepody) at five fertilizer rates. The full rate was calculated at 240/100/100 NPK lbs/acre equivalent over the entire growing season. Double rate was 2X this amount, with reduced rates of one-half, a quarter and one-eighth also applied (½, ¼ and ⅛ respectively). We doubled the amount of fertilizer used to a rate much higher than a realistic amount used by growers to observe an over fertilizing effect. However, we also observed that the optimal amount of fertilizer occurred at much lower rates and was varietal dependent. Therefore, we did not include the 2X rate in this remote sensing experiment. Ranger Russet and Russet Burbank had higher overall tuber production at the quarter fertilizer rate, while Shepody showed higher production at the half fertilizer rate. We expect that with even lower fertilizer applications we would see a downward trend, though exactly at what point this occurs is currently unknown.

Figure 6: Nutrient deprivation experiment setup for potato plants trial at AAFC greenhouse.

In preparation for the remote sensing measurements, and similar to Experiment #1, terminal leaflets (leaves) were extracted from the potato plants. Leaflet samples were placed in labelled bags according to the 3 potato varieties and 4 fertilizer treatment rates considered. The samples were transported from the AAFC greenhouse to the ATIC/i4Geo lab in an ice-packed cooler. Samples were only removed from the cooler for spectral measurement, then returned for cool storage.

3.2 Experiment #2 – Remote Sensing Protocols

For experimental consistency across Experiments #1 and #2, the same remote sensing lab setting, instrumentation, and individual plant set measurement protocols used in Experiment #1 (as described in §2.2) were also used in this Experiment #2, and therefore only modifications or additional protocols are described here, prior to presenting results.

3.3 Experiment #2 – Three Sets of Remote Sensing Tests

The remote sensing tests in Experiment #2 were similar in nature to Experiment #1 in that the same types of tests were performed, however, within each test, different specific protocols were examined, and it is only these differences that are described here. The outcomes from these tests also provided opportunity for confirming measurement protocols, assessing repeatability of experimental design and implementation, and assessing results, as Experiment #1 and Experiment #2 were performed at different years, and, while the same core personnel were involved (the 3 lead authors), different additional personnel assisted with Experiment #2 compared to the earlier year.

Our main remote sensing research question in Experiment #2 was, specifically: "Can potato plants be discriminated across the four different N rates, and for the three potato varieties?". As with Experiment #1, we had to test for plant transport and spectral measurement protocols to ensure experimental integrity and repeatability, in the same two ways: (i) plant arrangement, and (ii) measurement timing, prior to proceeding to the main test: (iii) fertilizer rate. Over 300 spectra were assessed in Experiment #2 and form the basis for recommendations, however, space only permits a representative sample of results, and so we show three examples here (Figures 7 – 9).

3.3.1 Experiment #2 –Test 1: Plant Optical Thickness: For Experiment #2, Test 1, we assessed plant arrangement and using the same general protocols as in Experiment #1 involving optically thick stacks [OTS], except that we now needed to consider additional potato varieties and treatment types. Given the larger requirement for spectral measurements in other tests [described below], and to keep within time step domains within each measurement set, and because we had definitive results from Experiment #1, in this Experiment #2 we limited the amount of testing of different numbers of leaf layers to assess the minimum to recommended number of layers, i.e. three to five [Experiment #1 tested up to 15 layers].

An example set of results is shown in Figure 7, confirming our previous research conclusion that a minimum of three OTS leaf layers is required, however, for consistency across all samples and given that additional layers do not pose operational constraints in terms of availability and timing, we recommend that 5 layers be used especially owing to greater variability of samples across potato varieties and growth stages, and therefore this was followed throughout this experiment and was the basis for overall recommendations.

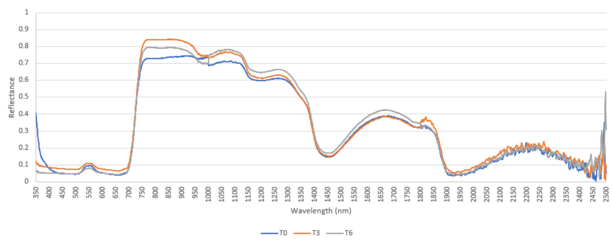

Figure 7: Reflectance spectra from different number of leaf layers (Ranger Russet, full rate, at T0)

3.3.2 Experiment #2 –Test 2: Within-Day Spectral Timing: For Experiment #2, Test 2, we tested measurement timing post-harvest with respect to time for transport from AAFC and measurement at the ATIC/i4Geo RS lab. In Experiment #1, we assessed times ranging to almost 3 days post-harvest [64 hours], concluding that 24 hours was an acceptable baseline. In this Experiment #2, therefore, we refined the testing to a finer time resolution within the front-end of the one-day period to test the more likely time steps post-harvest given the proximity of the facilities and the desire to minimize post-harvest timing. Further, as with Test #1 in this Experiment #2, given the much larger sets of samples for measurements given the different potato varieties and growth stages being considered, and that we had results from Experiment #1 to inform this new work, a focused experiment was required to avoid excessive / unnecessary measurement requirements so that the fertilizer experiments [test #3, below] could still be performed properly with respect to required time in the remote sensing lab. Thus, three time steps were tested, with reference to when the samples arrived at the ATIC/i4Geo lab: immediate measurement (T0), three hours after (T3), and six hours after (T6). The outcome from this set of tests was that we were able to confirm measurement integrity at all three time steps assessed (Figure 8) based on minimal spectral variation, thus providing robust and flexible options for spectral acquisition within the front-end of the preferred one-day measurement window. This provides excellent flexibility in terms of required time for measuring the various sample protocols in the lab. This is quite important given the greater number of samples and varieties that were needed to be tested in this Experiment #2, and – perhaps of greater importance – it confirms this aspect of the spectral measurement protocols for future planned testing that will likely have the same if not greater time requirement in the lab for supplied samples. Although not tested in this Experiment #2 [as it was already done in Exp #1], we do note that if time beyond +6 hours is required, it should be acceptable. The focus of this test in Exp #2 was to ensure that the period during which the vast majority of spectral measurements would be acquired – the first 6 hours post-reception – is viable. This is also important for practical and operational considerations involving lab availability and personnel.

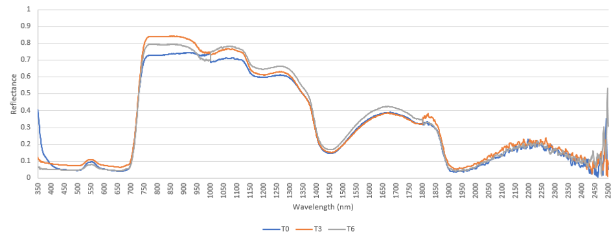

Figure 8: Reflectance spectra at times T0, T3, and T6 (Russet Burbank, full fertilizer rate).

3.3.3 Experiment #2 –Test 3: Assessing Nutrient Deprivation Levels for Different Potato Varieties: Test 3 in Experiment #2 involved the main application assessments of nutrient deprivation. Informed by the results from Tests 1 and 2 in terms of spectral measurement protocols and timing, we now tested for nutrient deprivation involving three potato varieties and four treatment levels. This generated a large set of results for which we report a representative set of outcomes given the consistency across results. As shown in Figure 9, it was clear that we can distinguish amongst the treatment levels tested for all varieties. The near-infrared (NIR) and part of the short-wave infrared (SWIR) portions of the spectrum (NIR to SWIR λs ~700nm-1800nm) was optimal for discrimination. However, the visible portion (400-700nm) showed poor discrimination (which we informally also confirmed as all the samples looked similar by human vision), as did longer SWIR λs (> 1800nm, even after factoring for higher measurement noise).

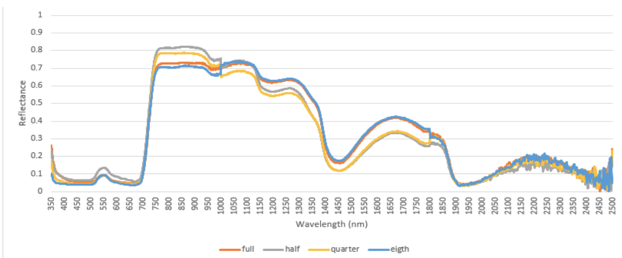

Figure 9: Reflectance spectra at different Nitrogen fertilizer rates (Ranger Russet, T0, 5 layers).

4. Discussion

At the commencement of the current project there were fundamental questions on sample collection, preservation and stability. Typical field testing involves collecting petioles for processing in the lab. From these two experiments, we have established the necessary protocols for plant preparation, growth, treatment, harvesting, and transport that are suitable for a range of remote sensing spectral tests. In the same way, we have also established reliable and operational remote sensing laboratory protocols. These have been tested and proven across two full experiments that included robustness of experimental design (e.g. we could test different aspects of the agricultural plant growth and treatments using these protocols), and also, repeatability, given these two experiments were performed over different years and with different plant samples.

In terms of remote sensing spectral protocols, from our extensive series of measurements we recommend using 5-layers of potato leaves in optically thick stacks to ensure proper target spectral acquisition. These measurements are viable within the first 24 hours, possibly longer, as our results from following days showed some time-based variability, although we did not perform higher temporal resolution tests within the 24 – 48 time range.

In terms of plant stress and nutrient deprivation, across both experiments we found good consistency in terms of the spectral wavelength ranges that possess preferred discriminatory value. In all three tests, there appeared to be greatest distinction amongst targets in the near-infrared (NIR) and part of the short-wave infrared (SWIR) portions of the spectrum (~700nm-1800nm). Less discrimination was evident in the visible portion (400-700nm), consistent with visual appearances of these various samples throughout the experiment. At longer SWIR λs there appeared to be less discrimination, despite the greater measurement noise. These results were based on qualitative assessment of spectral variation in terms of magnitude and shape of spectral curves as graphed in the various figures. Future tests could refine this to include statistical assessments and comparisons, similar to Coulibali et al. (2020). It would also be useful to compare results generated from a leaf reflectance model such as PROSPECT.

5. Conclusion

This study demonstrates the potential of hyperspectral remote sensing to detect nutrient deprivation and vegetation stress in potato plants within minimal input agricultural systems (MIAS). Through two independent laboratory experiments, we validated the effectiveness of remote sensing protocols in distinguishing plant stress levels associated with varying nitrogen (N) inputs. Key findings include the identification of optimal leaf density for spectral measurements and the timing for sample assessments, ensuring reliable data acquisition within a 24-hour window post-harvest.

These initial results indicate that viable reflectance spectra can be obtained from optically thick stacks comprising 3 to 5 leaf layers, with 5 layers recommended. Measurements should always be obtained at the earliest priority but appear to be viable within a one-day period, possibly longer. It is feasible to provide these numbers of samples (layers) within this timeframe in terms of plant harvesting, the logistics of transport, and spectral measurement, given reasonable coordination amongst sites and personnel. Using these recommended protocols, we concluded there is a strong basis to pursue the use of remote sensing further as it clearly appears to provide information that is useful towards the design and implementation of minimal input agricultural systems.

Based on the very high level of experimental control, isolating the only differences as being due to exposure to different levels of nutrient deprivation, we conclude the ability to discriminate different levels of Nitrogen treatment both within and across all three potato varieties. The results consistently highlighted the near-infrared (NIR) and short-wave infrared (SWIR) regions (700-1800nm) as the most effective spectral ranges for discriminating among different N treatments. This study establishes foundational remote sensing protocols for MIAS, establishing the way for future field and airborne studies aimed at optimizing fertilizer application while maintaining crop yield and quality. The successful application of hyperspectral remote sensing in this context supports the broader goal of developing sustainable agricultural practices with minimal environmental impact.

Acknowledgements

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