# A framework for sensor-based nitrogen management using nutrient dilution and sufficiency

**André Colaço**, Glenn Fitzgerald, Perry E M[2,4] and Bramley R G V[1]

[1] CSIRO, Waite Campus, Locked Bag 2, Glen Osmond, SA 5064. *andre.colaco@csiro.au
[2] Centre for Agricultural Innovation, School of Agriculture and Food, Faculty of Veterinary and Agricultural Sciences, The University of Melbourne, VIC 3010.
[3] Agriculture Victoria Research, Department of Jobs, Precincts and Regions, 110 Natimuk Road, Horsham, VIC 3400.
[4] Agriculture Victoria Research, Department of Jobs, Precincts and Regions, 1 Taylor Street, Epsom, VIC 3551.

## Abstract
This study presents a sensor-based mid-season nitrogen (N) recommendation approach developed using nutrient dilution theory and supported by on-farm experimentation. Crop reflectance and LiDAR sensors were used in combination to predict crop biomass and plant N concentration. The predicted crop traits are the input to an N recommendation approach aimed at raising the crop from its current N concentration to the optimal N concentration associated with a target crop biomass. The approach is demonstrated in a commercial 64 ha wheat paddock in the mid-north of SA. This work will help farmers to explore nutrient sufficiency strategies as an option for N management.

## Keywords
Crop reflectance sensor; LiDAR; canopy nitrogen index; Future Farm project.

## Introduction
Nitrogen (N) management approaches available to farmers have historically been based on either generalized crop response models or underpinned by a mass balance calculation in which information about nutrient demand and supply are critical. These are often difficult to predict. An alternative strategy, arguably less common amongst farmers and their advisors, builds on the theory of N dilution and critical nutrient level. Here, the main goal of applying N fertiliser is to guarantee adequate plant nutrition based on a target plant N concentration (Lemaire et al. 2019). By focusing on the diagnosis of plant mineral nutrition (i.e. actual crop nutrient status), this approach overcomes assumptions relating to soil-plant interactions affecting plant N uptake and crop N response which may limit the success of other common N management strategies. Despite being supported by a vast scientific literature (Lemaire et al. 2019), this approach has not been widely adopted at the farm level as it requires in-field measurements of crop biomass and plant N concentration, both of which can be time consuming and costly. Advances in digital technologies have shown potential to overcome these issues as they allow the non-destructive assessment of these features at scale (e.g. Colaço et al. 2021). The objective of this work was to implement an 'N sufficiency' framework to inform mid-season N recommendations in wheat using sensor technology. The approach is informed by LiDAR (light detection and ranging) and reflectance sensors and supported by on-farm experimentation.

## Methods
*Field experimental design*
A 64 ha wheat paddock in the mid-north region of South Australia was used for this study during the 2019 season, with N strips implemented across the paddock to create a range of N availability for the crop (Figure 1). Applied N rates were 11, 57, and 141 kg N $ha^{-1}$ in the 'minus', 'normal paddock' and 'rich' treatments. The field was also classified into three management zones based on a digital soil survey and historical yield maps. At the beginning of crop stem elongation (GS31), the field was scanned with a LiDAR sensing system (SICK, LMS-400) for crop height assessment and a Crop Circle sensor (Holland Scientific, ACS-435) for normalized difference red edge (NDRE) assessment.

At the time of crop sensing, 21 plant cuts (two rows of 1 m length cut at the ground level) were collected in targeted locations (Figure 1) for dry biomass and plant N concentration measurements.

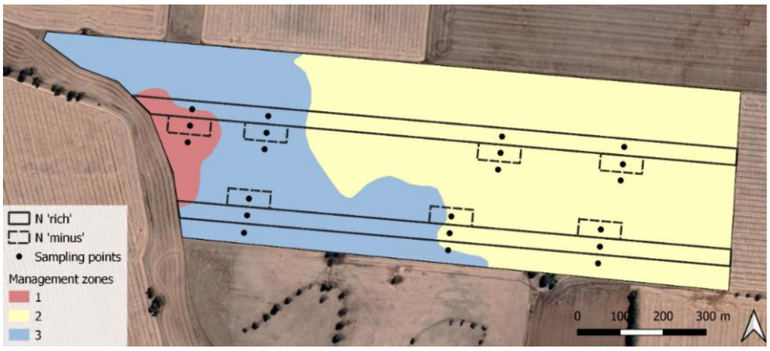


**Figure 1. Trial design on a 64 ha paddock featuring N-rich and N-minus strips and plant sampling locations spread across N treatments and management zones.**

*N recommendation framework*

An N recommendation framework based on N dilution and critical N level was used where the goal of mid-season fertilisation is to raise the crop from its current N concentration to the optimal N level associated with a target crop biomass. This is achieved by means of an established N dilution model, on-farm experimentation and sensor estimates of biomass and N concentration. Figure 2 illustrates the approach with a hypothetical N dilution plot. The target biomass is the one associated with unlimited N supply assessed in-situ using an N-rich strip. In this study, the target biomass for each management zone was the median biomass of the N-rich area in each zone (Figure 1). The target N concentration is the optimal N concentration associated with the target biomass and derived from an established N dilution model. For this study, the N dilution curves developed by Fitzgerald et al. (2010) were used with the target N concentration set to 95% of the maximum N concentration curve (equivalent to a canopy nitrogen index of 0.95). The fertiliser efficiency is the proportion of applied fertiliser N that is absorbed by the plant and was calculated using sensor estimates of N uptake from the 'N-minus' and 'paddock' treatments (the sensor estimates of plant N concentration and crop biomass, which are used to calculate plant N uptake, are described below).

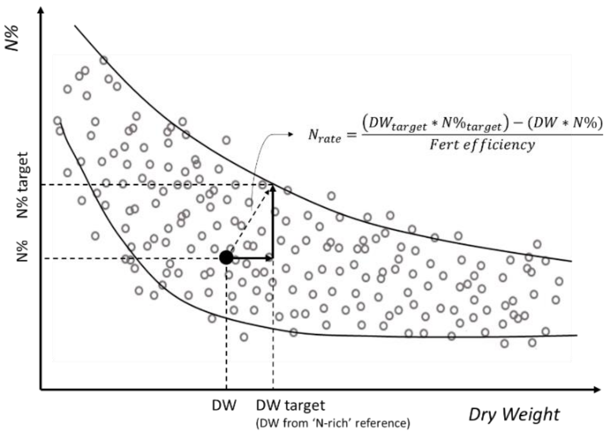


**Figure 2. Hypothetical N dilution plot and an N recommendation approach based on raising the crop from current N concentration to the optimal N level associated with a target crop biomass.**

*Sensor estimates of crop biomass and N concentration*

Crop biomass and plant N concentration are the inputs needed to inform the N recommendation as illustrated in Figure 2. Crop biomass was predicted using a linear regression between LiDAR-derived crop height and dry biomass measured at the target sampling points. A map of crop biomass can then be generated for the entire paddock using the mapped LiDAR data (Colaço et al. 2021). The prediction of N concentration followed a two-step process. First, the biomass normalized vegetation index (BiNVI), a multi-sensor index, was used to predict the canopy nitrogen index (CNI) using a linear regression based on the sampling points. The CNI is an index used to benchmark the crop N nutrition against maximum and minimum N concentration limits expected for a particular crop biomass value, normally ranging between 0 and 1 (see Fitzgerald et al. 2010 for more details). The ground truth CNI was calculated at each plant cut using biomass and N concentration data and the N dilution boundaries from Fitzgerald et al. (2010) (Figure 3a). The BiNVI was also calculated at each sampling point using NDRE from the Crop Circle sensor and crop height from the LiDAR sensor (Figure 3b). The upper and lower boundaries in Figure 3b were derived from the mapped sensor data across the entire paddock. Once CNI is predicted using a calibrated equation from BiNVI, plant N concentration can be calculated using the LiDAR derived biomass information ($N\% = (N_{max} - N_{min}) \times CNI + N_{min}$; where $N_{max}$ and $N_{min}$ are linear functions of crop biomass (the lower and upper lines in Figure 3a) from established N dilution models); note in Figure 3a that if CNI is known, one can calculate N concentration based on biomass information.

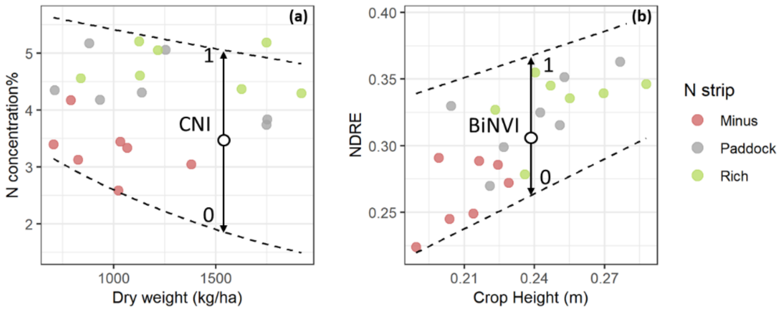


**Figure 3. Calculation of (a) the 'canopy nitrogen index' (CNI) for each sampling point in the 'N-minus', 'paddock' and 'N-rich' treatments using established N dilution curves (from Fitzgerald et al., 2010; dotted dark lines); and (b) the derivation of a sensor-based index used to predict the CNI, the 'biomass normalized vegetation index' (BiNVI) using NDRE from a reflectance sensor and crop height from a LiDAR sensor and upper and lower limits (dark dotted lines) derived from the NDRE x Crop Height mapped data across the studied paddock.**

## Results

The dry biomass calibration from LiDAR crop height achieved an $R^2$ of 0.63 (Colaço et al. 2021). Coupled with the CNI-BiNVI relationship ($R^2$=0.71, data not shown), the resulting plant N concentration predictions had an $R^2$ of 0.60 (data not shown) based on the ground truth sampling data. Maps of plant biomass and N concentration were then developed and used to generate a mid-season N recommendation map (Figure 4). In Figure 5, the data of predicted crop biomass and N concentration at each map pixel is plotted against each other along with the upper and lower N dilution curves from Fitzgerald at el. (2010) to illustrate the approach. Overall, two rules work simultaneously to determine the N rate to apply: N rates increase with lower CNI, and N rates increase with higher crop biomass response (in Figure 4 the response index was calculated as RI = target biomass / current biomass).

## Discussion

The proposed framework successfully combined N dilution and critical nutrient level theories with sensor technology and on-farm experimentation. Its implementation depends, however, on reliable and previously developed sensor calibrations for crop biomass and CNI predictions and established N dilution curves from which adequate critical N concentrations can be derived; both these issues are still important research challenges. For example, the critical N concentration is defined as the one associated with maximum crop growth, which may or may not be adequate for dryland cropping systems prone to terminal drought. However, the proposed framework does allow adjustments of both the target crop biomass and the target CNI to accommodate issues related to weather and farmer's attitude to risk. Combining information on stored soil water into this approach would likely increase its applicability across different rainfall regions. Whilst this work demonstrates the operational feasibility of an ‘N sufficiency’ strategy through sensor technology, future research should continue to evaluate it as an option for N management in Australian farming systems.

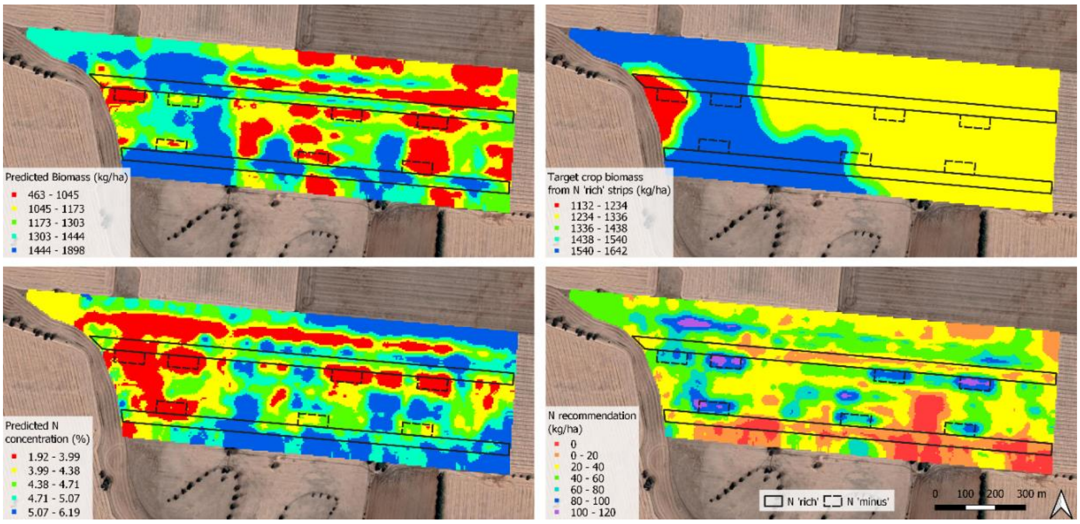


**Figure 4. Maps of predicted crop biomass and plant N concentration from crop reflectance and LiDAR sensors (left) and target crop biomass from N-rich areas and the mid-season sensor-based N recommendation (right).**

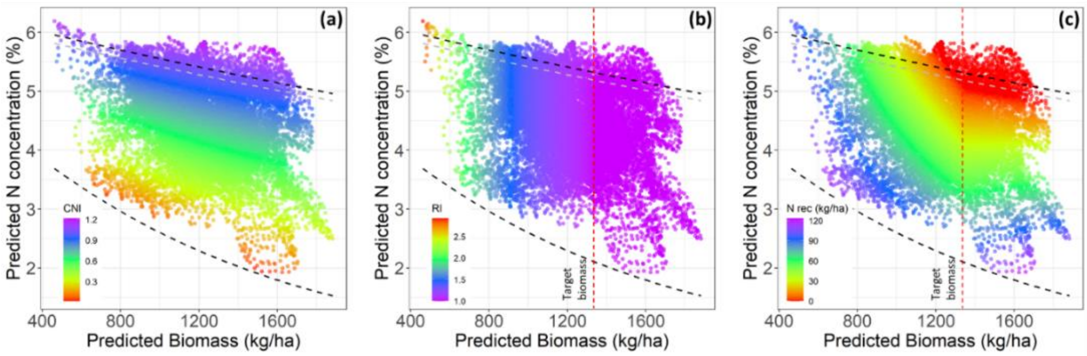


**Figure 5. Predicted plant N concentration vs predicted crop biomass across the evaluated paddock with points coloured by the canopy nitrogen index (CNI; a), biomass response index (RI = N rich biomass / current biomass; b) and the recommended N rate (c). Dark dotted lines: ‘global’ boundaries from the N dilution plot from Fitzgerald et al. (2010); grey dotted line: target N concentration for fertilization (CNI = 0.95); red dotted line: target crop biomass at GS31 = the median biomass in the ‘N-rich’ strip (note that for this illustration a single target biomass was used for the entire paddock area).**


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