
# Remote sensor estimation of Cover Crops macronutrients uptake aiming to support farmers' fields nutrients management.

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*The introduction of cover crops/catch crops into the cash crops field rotation system is increasing year after year and becoming common practice among farmers. In Europe, this is especially driven by regenerative agriculture practices and government subsidies. But the introduction of cover crops changes the dynamics of nutrients in the field cultivation system, as legumes cover crops can biologically fix atmospheric nitrogen to the soil, bring nutrients from the sub-soil to the surface, temporally sequestrate nutrients and most importantly, bring remaining nutrients from one cash crop season into the next one. Based on that, aiming for precise crop nutrition management and fertilizer recommendations, it is very important to know the amount of nutrients taken up by cover crops in a simple, scalable and affordable way. To achieve this, the objective of this research was to calibrate a remotely acquired sensor-based vegetation index against cover crops biomass and macronutrients uptake. During the fall of 2024 and 2025, plots seeded with single crover crops species (Bristle oats, Phacelia, Berseem clover and Mustard) but also plots containing mixes of different species have been established. The study was conducted in Lower Saxony and North Rhine-Westphalia - Germany. From early development until winter frost, the plots were periodically measured with a handheld spectrometer (Yara N-Sensor technology), after being sampled for above ground fresh matter. Samples were dried, and then laboratory analyzed for macronutrients concentration. Nutrient results were adjusted to the dry matter content, and nutrients uptake per hectare was calculated. From the sensor, the spectral index was calculated and related to fresh/dry matter and macronutrients uptake. Results showed significant correlation between biomass and sensor readings, as well as nutrients uptake and sensor vegetation index. This demonstrates that the amount of biomass and its nutrient content can be field-wise remotely predicted by a vegetation sensor.*

***Keywords.***
*Cover crops, Macro nutrients, Remote sensing, Crop nutrition plan.*

## Introduction

Cover crops, also known as catch crops or pre-crops, play a crucial role in sustainable agriculture practices. The benefits of the long-term use of cover crops are well documented; Cover crops have been shown to improve soil physical (Basche et al., 2016), chemical (Kwiatkowski et al., 2020), and biological properties (Basche et al., 2016). Also, protect fields from soil erosion and run-off (Derpsch et al., 1986) preventing the eutrophication of lakes and rivers. Suppress weeds (Brust et al., 2014), mitigate nutrient leaching into groundwater and increase the nutrient use-efficiency of farming systems (Dabney et al., 2001). Due to these agronomic, economic and ecological benefits, cover crops are frequently integrated into crop rotations to enhance the land productivity of the main crop while complying with environmental aspects.

The introduction of cover crops into the cash crops field rotation system is increasing year after year and becoming common practice among farmers. In Europe, this is especially driven by regenerative agriculture programs, as promoted by major food chain companies and government subsidies. The widespread cultivation of winter cover crops is further boosted by incentives from the common agricultural policy of the European Union (European Commission, 2017).

However, the introduction of cover crops can change the dynamics of nutrients in the farming system through the biological fixation of atmospheric nitrogen (Thorup-Kristensen, 1993) from leguminous cover crops, nutrient mobilization from the subsoil to the topsoil (Han et al., 2021), temporal sequestration of nutrients and subsequent mineralization which enables the transfer of residual nutrients from one cash crop season into the next one (Thomsen & Christensen, 1999; Wander et al., 1994). Although the amount of nutrients that can be recycled and made available from cover crops to the subsequent cash crop depends on the amount of nutrients taken up by the cover crops and the mineralization of the incorporated biomass. European legal frameworks like the German fertilizer ordinance (BMJV, 2017) recommend reductions in N fertilizer rate solely based on the functional groups of previous cultivated cover crops, what appears to be not adequate for a precise field nutrient management.

Previous studies on sensor-based measurement of cover crops consistently show that proximal and remote sensing technologies can reliably estimate key biophysical properties such as biomass, nitrogen content, and ground cover, though accuracy depends on crop type, growth stage, and environmental conditions. Hively et al. (2009) demonstrated that vegetation indices derived from multispectral imagery (e.g., NDVI) correlate well with cover crop biomass and nitrogen uptake, while Goffart et al. (2021) and Futerman et al. (2023) expanded on this by highlighting the value of high-resolution satellite and UAV data for capturing spatial variability and improving field-scale monitoring. Holzhauser et al. (2022) and Kümmerer et al. (2023) further showed that integrating multisensor data (e.g., optical and radar) and advanced modeling approaches enhances robustness under challenging conditions such as cloud cover or dense canopies, enabling more consistent estimation of cover crop performance. Overall, these works indicate that sensor-based approaches provide scalable, non-destructive alternatives to traditional sampling, but require calibration and adaptation to specific species mixtures and management contexts to achieve reliable results.

Taking this into consideration and aiming for precise crop nutrition management and fertilizer recommendations, it is essential to know the amount of nutrients taken up by cover crops in a simple, scalable, and affordable way. To achieve this, the objective of this research was to calibrate a remotely acquired sensor-based vegetation index (Yara N-Sensor) against cover crops biomass and macronutrients (N, P, K, Ca, Mg, and S) uptake.

## Material and Methods

During the fall of 2024 and 2025, plots with single cover crops species (Bristle oats, Phacelia, Berseem clover and Mustard) and mixes of different species were established in three fields (hereafter referred to as Field 1, Field 2 and Field 3). Fields 1 and Field 2 are located in the “Deutsche Saatveredelung” (DSV Seeds) research station at Asendorf (52°45′48.4″N 9°01′24.3″E), Lower Saxony - Germany. Field 3 was established at the Yara Research Center Hanninghof located at Duelmen, North Rhine-Westphalia - Germany (51°50'23.14"N 7°15'15.99"E). Both locations are circa 50 m above sea level; the mean annual temperature is 9°C, and the mean annual precipitation is about 800 mm. The local soils are classified as Stagnic-Cambisol in Asendorf and Podsol-Pseudogley at Duelmen.

Before having cover crops, field 1 had silo maize as a cash crop in 2024 and 2025, while fields 2 and 3 had winter cereals as the previous crop. No fertilization was carried out, aiming to nourish the cover crops. Only the residual fertilizer from previous commercial crops was available. Table 1 summarizes the various cover crops and Mixes in the fields, including their composition and sampling dates, with the number of plots per cover crop in each of the fields in brackets.

**Table 1: Cover Crops and Sampling dates**

| Fields | # cover crop | Sowing dates | 2024 sampling dates<br>(Plots per cover crop) | 2025 Sampling dates<br>(Plots per cover crop) |
|---|---|---|---|---|
| Field 1 | Yellow Mustard<br>Phacelia<br>Bristle oats<br>Berseem clover<br>[1] Mix 1<br>[2] Mix2 | 07.08.2024<br>25.08.2025 | 17.09.2024 (1)<br>15.10.2024 (1)<br>1.11.2024 (1)<br>17.12.2024 (1) | 16.9.2025 (2)<br>30.9.2025 (2)<br>21.11.2025 (2)<br>02.12.2025 (2) |
| Field 2 | Mix 2<br>[3] Mix 3<br>[4] Mix4<br>[5] Mix 5<br>[6] Mix 6<br>[7] Mix 7 | 06.08.2025 | | 02.09.2025 (2)<br>16.09.2025 (2)<br>30.09.2025 (2)<br>21.10.2025 (2)<br>11.11.2025 (2) |
| Field 3 | Mix 2<br>Mix 4 | 03.10.2024 | 04.12.2024 (4) | |

# The cover crops were provided by DSV seeds.

[1] Mix 1 is a mixture of yellow mustard, Phacelia, Bristle Oats and Berseem clover).

[2] Mix 2 with a commercial name of MaisPro is a mixture of Abyssinian cabbage, Field pea, Linseed, deep-rooted radish, Persian clover, Phacelia,Niger, Common Vetch, Sunflower, Sorghum, Red cover, Serradella, and white clove).

[3] Mix 3 with commercial name of N_Fixx, is a mixture of Phacelia, Linseed, Sunflower, Niger, Sorghum, Field pea, Common vetch, Egyptian clover, Persian clover, and Sparrose clover.

[4] Mix 4 with a commercial name of AquaPro is a mixture of Phacelia, Linseed, Sunflower, Bristle oat, Niger, and Sorghum).

[5] Mix 5 with a commercial name of Rigol is a mixture of Phacelia, Linseed, Sunflower, Bristle oat, Niger, Common vetch, Deep-rooted radish, Abyssinian cabbage, Fagopyrum tataricum, Falseflax, and Persian clove).

[6] Mix 6 with a commercial name of Betamaxx is a mixture of Phacelia, Linseed, Bristle oat, Niger, Field pea, Common vetch, Serradella, Egyptian clover, and blue lupin).

[7] Mix 7 with a commercial name of Vitamaxx is a mixture of Phacelia, Linseed, Bristle oat, Niger, Deep-rooted radish, Abyssinian cabbage, Falseflax, Fagopyrum tataricum, and Mustard).

From early development until winter frost, the plots were periodically measured with a handheld spectrometer (Yara N-Sensor technology). The spectrometer measures the reflectance in the spectral range of 400 to 1000 nm with a 10 nm spatial resolution in nadir view to the crop canopy. For each treatment, four measurements were taken from each azimuth to avoid solar and shadow effects and finally repeated twice. After the spectral measurements, the measured area was sampled (1m$^2$ of aboveground biomass was harvested per treatment and replication) for fresh matter. Samples were dried (at 65°C until a constant weight) and then laboratory-analyzed for macronutrients concentration. Nutrients' concentration results were adjusted to the dry matter content and nutrients uptake per hectare calculated. From the sensor, the spectral index (Link et al., 2003) was calculated and related to fresh/dry matter and macronutrients' uptake.

To use the sensor vegetation indices aimed at macro nutrient prediction, two approaches were used. Firstly, sensor vegetation indices from each cover crop were used for predicting macro nutrient uptake from the same cover crop treatment based on linear regression. We refer to this method as the "cover-crop specific model approach". This approach was only validated for Mix 2 for which there was sufficient data for both calibration and validation. Secondly, the possibility of a generalized model for each nutrient uptake for all cover crops combined was tested. A leave-one-cover-crop-out cross-validation approach was used. That means, each cover crop was excluded in turn from model calibration through linear regression. The excluded cover crops were used to test how the model estimates a particular nutrient uptake. We refer to the second method as the "generalized model approach". Both approaches were evaluated using the coefficient of determination ($R^2$) and the root mean square error (RMSE).

## Results and discussion

Figure 1 shows the observed biomass development for the cover crops in Field 1 during the Fall season in 2024 while Figure 2 shows the biomass development for the same field in 2025.

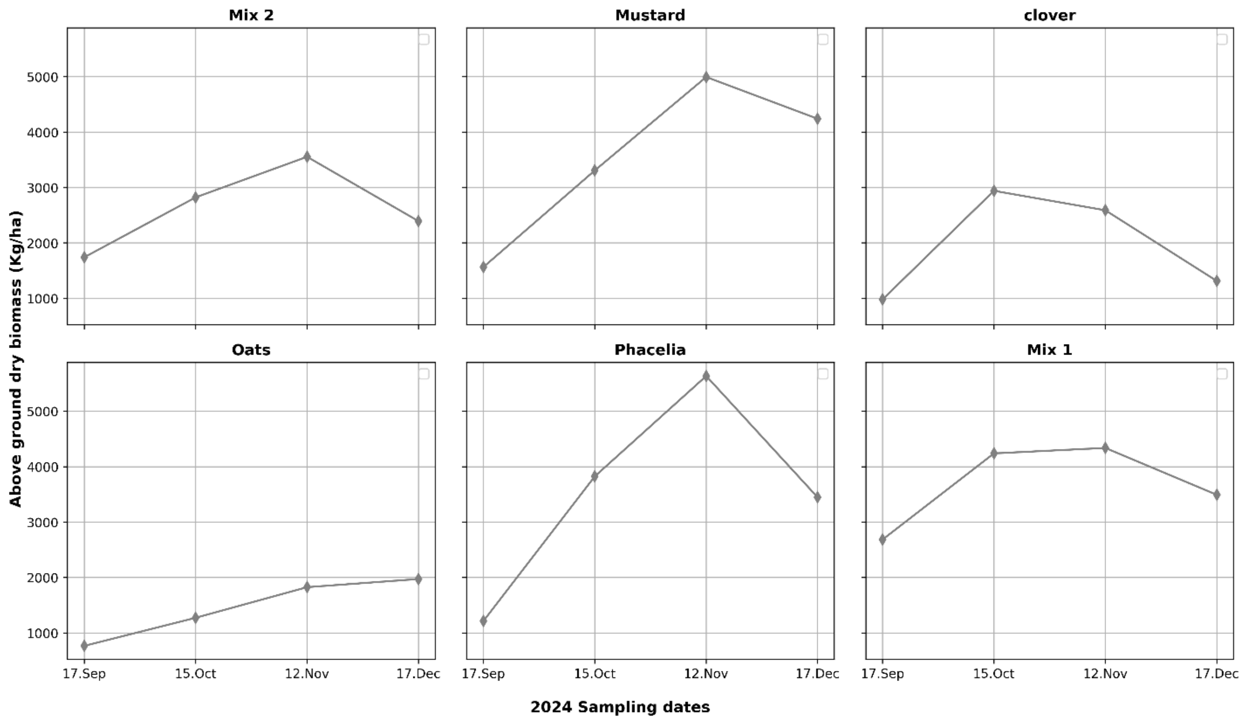


**Figure 1: Biomass development for Cover crops in Field1 (2024)**

Figures 1 and 2 (Field 1) show biomass peak accumulation around November and drops thereafter due to senescence resulting from winter frost (temperatures below 0ºC). As cover crops sown in temperate regions typically have a relatively small vegetative growth window of few months before the onset of winter, the sowing date has a great impact on the peak of biomass accumulation. The peak biomass accumulation for cover crops in Field 1 in 2025 was much lower than those in 2024 because of late sowing. In 2025, there were some differences between the above-ground dry biomass of the two replications sampled, respectively plot 1 (P1) and plot 2 (P2) for each of the cover crops. These differences can relate to in-field variabilities between the plots due to soil properties and germination rate, for instance. In Field 1, the cover crops can be ranked according to their biomass accumulation ability as Phacelia>Mustard>Mix 1>Mix 2>Clover>Oats. Cover crops with high biomass accumulation are also generally relevant as catch crops (catching residual nutrients and mitigating leaching) and are more capable of protecting the soil against runoff erosion.

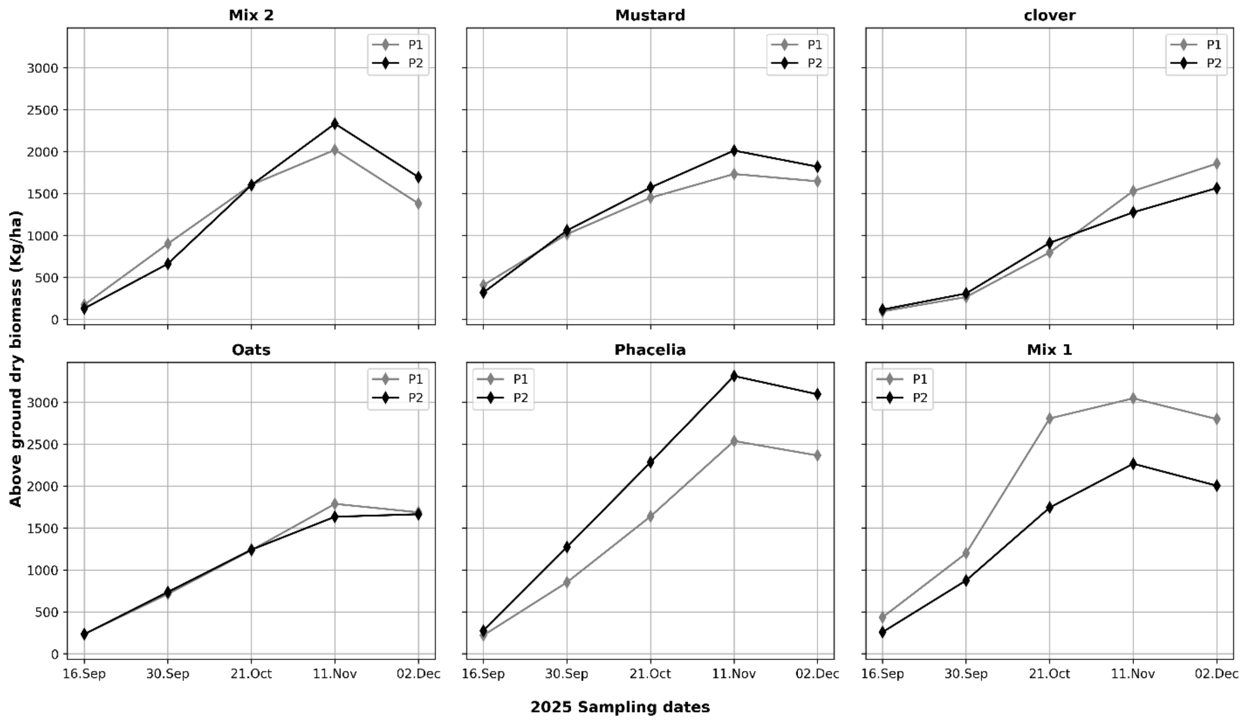


**Figure 2: Biomass development for cover crops in Field 1 (2025)**

Figure 3 shows the observed biomass development for the cover crops in Field 2 during the Fall season in 2025. The cover crops were sown in two plots indicated as (P1 and P2 as seen in the legend of Figure 2). Unlike the case of Field 1, in 2025, where late sowing limited biomass development, the cover crops in Field 2 were sown earlier and attained full vegetative development between October and November. All the cover crops in Field 2 developed their peak biomass by October except for Mix 4, which developed up to November. Under full development, the cover crops in Field 2 accumulated a relatively higher biomass as compared to the cover crops in Field 1. Besides sowing dates, the peak biomass accumulation also depends on other factors like the initial content of nutrients in the soil that is related to the previous cash crop (different from Field 1) and the nutrient scavenging ability of the cover crops.

The observations showing the maximal biomass accumulation in Figures 1, 2 and 3 are important, because they indicate the time of maximum biomass accumulation in the season and so can be used for calculating the amount of the macro-nutrients taken up by cover crops. The amount of macro nutrients taken up by cover crops is relevant for field nutrient management. This is because it provides the basis for estimating the amount of macro nutrients that can be mineralized and made available to the subsequent cash crops.

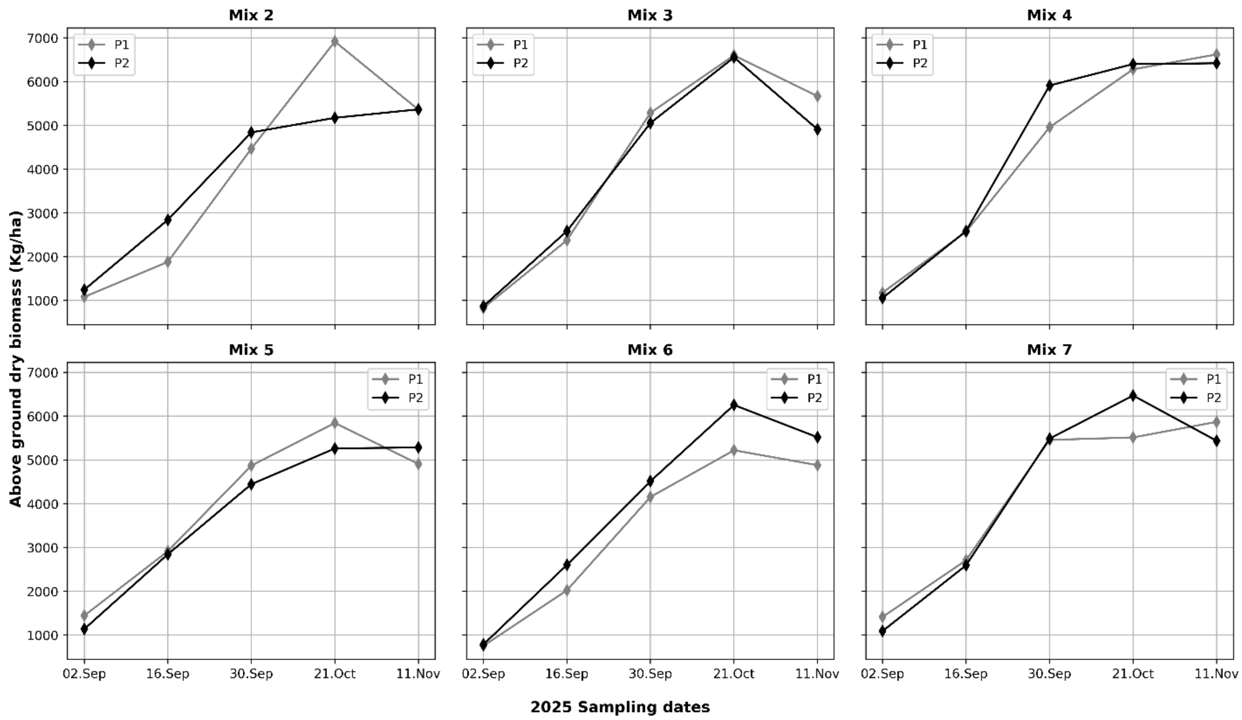


**Figure 3: Biomass Development for cover crops in Field 2 (2025).**

## Macro nutrient uptake prediction (Cover-crop specific model approach)

Figure 4 shows cover crop treatments data as sensor-predicted macro nutrient uptake with the corresponding measurements from the sampled biomass macro-nutrients, while Table 2 shows the coefficient of determination ($R^2$) and the root mean square error (RMSE) as a means of assessing the feasibility of the sensors to predict macro nutrient uptake from the cover crops. The RMSE gives an indication of the accuracy of the sensor predictions in Kg ha-¹ of the predicted nutrient. The Lower the RMSE value, the more accurate the predictions. For each macro nutrient, $R^2$s ≥ 0.6 are marked in bold to indicate the cover crops for which the sensor predictions are reasonably good. The results in Table 2 underscore the relative difficulty in predicting macro nutrient uptake from Mixes as compared to single-specie cover crops. Apart from Oats, the $R^2$ values indicate a generally good feasibility in predicting the macro nutrient uptake from the other single-specie cover crops (Mustard, Clover, and Phacelia).

Besides, the feasibility of predicting macro nutrient uptake from the sensor vegetation index, Figure 4 enables a direct comparison of the nutrient uptake abilities of the studied cover crops. For instance, based on their maximum nitrogen uptake, the cover crops can be ranked as Mix 3 (144 kg/ha) > Mix 6 (112 kg/ha) >Mix 5 (105 kg/ha) > Mix 4 (100 kg/ha) > Mix 2 (97 kg/ha) > Mix 7 (91 kg/ha) > Clover (83 kg/ha) > Phacelia (76 kg/ha) > Mix 1 (69 kg/ha) > Mustard (60 kg/ha) > Oats (35 kg/ha). Apart from residual nitrogen taken from the soil, the reported values might also include nitrogen resulting from the biological fixation of atmospheric nitrogen where legumes are present in the cover crop.

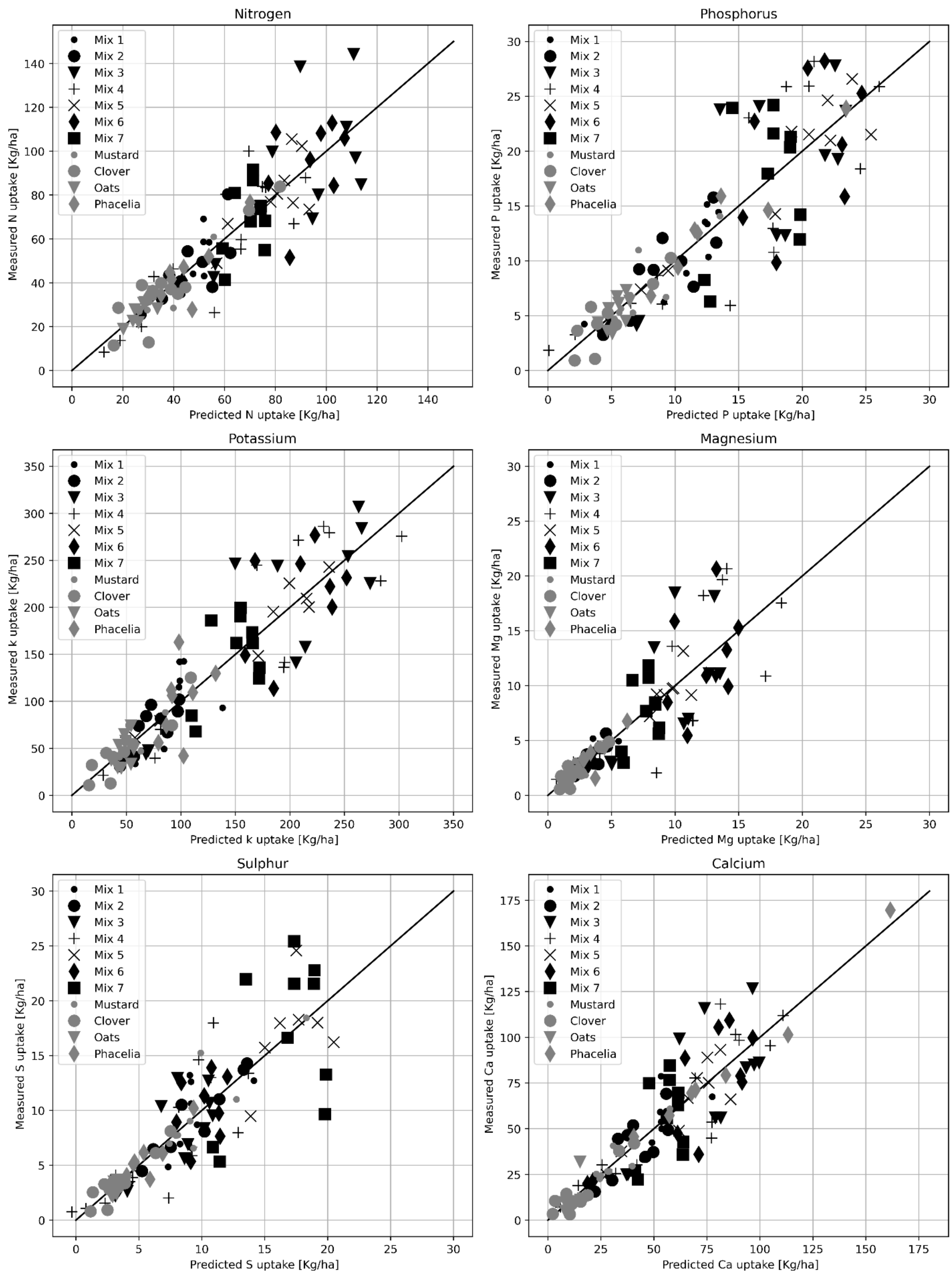


**Figure 4: Comparison of sensor-predicted and measured Macro nutrient uptake of cover crops.**

The mixes perform better for nitrogen uptake than single species due to the synergistic action of legumes and deep-rooted cover crop species. Due to a tendency for Nitrogen (N) in the nitrate form to leach to deeper layers, cover crop species with a high root biomass or density in deeper layers have been observed to be better nitrogen scavengers (Thorup-Kristensen, 2001). To understand the impact of roots on N uptake, Heuermann et al. (2019) investigated the impact of root architecture on the N scavenging ability of the Mix 1 and its components (Mustard, Phacelia, Bristle Oats and Berseem) during the 2015 cropping season in Asendorf. They ranked the crops according to their root biomass in the subsoil as Phacelia > Mix 1 > Mustard > Bristle oats > Berseem clover. Our results show a similar pattern for the maximum N uptake (Clover (83 kg/ha) > Phacelia (76 kg/ha) > Mix 1 (69 kg/ha) > Mustard (60 kg/ha) > Bristle oats (35 kg/ha), with clover topping the rank due to symbiotic nitrogen fixation.

**Table 2: Crop specific model calibration assessment**

| Nutrient | N | | P | | K | | Ca | | Mg | | S | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cover Crop | $R^2$ | RMSE kg/ha | $R^2$ | RMSE kg/ha | $R^2$ | RMSE kg/ha | $R^2$ | RMSE kg/ha | $R^2$ | RMSE kg/ha | $R^2$ | RMSE kg/ha |
| Mix 1 | **0.68** | 8.0 | **0.74** | 1.9 | 0.28 | 30.8 | 0.28 | 30.8 | **0.67** | 0.7 | 0.52 | 2.34 |
| Mix 2 | 0.58 | 9.7 | **0.62** | 2.2 | 0.59 | 14.5 | 0.59 | 14.5 | **0.73** | 0.7 | **0.91** | 1.13 |
| Mix 3 | 0.41 | 24.8 | 0.54 | 5.4 | **0.67** | 50.3 | **0.67** | 50.3 | 0.34 | 4.3 | 0.48 | 2.50 |
| Mix 4 | **0.72** | 14.6 | **0.71** | 5.0 | **0.77** | 46.8 | **0.77** | 46.8 | **0.60** | 4.4 | **0.63** | 3.23 |
| Mix 5 | 0.53 | 11.1 | **0.86** | 2.4 | **0.94** | 14.6 | **0.94** | 14.6 | **0.83** | 1.2 | **0.72** | 3.22 |
| Mix 6 | **0.66** | 16.2 | **0.65** | 5.2 | **0.72** | 42.8 | **0.72** | 42.8 | 0.55 | 3.8 | **0.60** | 2.49 |
| Mix 7 | 0.16 | 13.4 | 0.19 | 5.5 | 0.27 | 36.2 | 0.27 | 36.2 | 0.14 | 2.6 | 0.21 | 6.14 |
| Mustar | **0.80** | 4.7 | **0.68** | 2.7 | **0.61** | 11.0 | **0.61** | 11.0 | **0.74** | 0.8 | **0.69** | 2.23 |
| Clover | **0.85** | 8.1 | **0.75** | 1.4 | **0.84** | 12.8 | **0.84** | 12.8 | **0.79** | 0.6 | **0.86** | 0.81 |
| Oats | **0.61** | 3.3 | 0.32 | 1.1 | 0.17 | 14.0 | 0.17 | 14.0 | **0.35** | 0.4 | 0.16 | 0.51 |
| Phacelia | **0.69** | 7.8 | **0.9** | 1.6 | 0.17 | 33.9 | 0.17 | 33.9 | **0.71** | 0.8 | **0.78** | 0.96 |

From Figure 4 it can also be seen that the peak phosphorus (P) uptake follows the descending order; Mix 6 (18.2 kg/ha) > Mix 4 (28.1 kg/ha) > Mix 3 (27.7 kg/ha), Mix 5 (26.5 kg/ha), Phacelia (23.8 kg/ha) > Mix 2 (22.5 kg/ha) > Mix1 (15.1 kg/ha) > Mustard (14.08 kg/ha) >Mix 7(14 kg/ha) >Cover (10.26 kg/ha) > Oats (7.33 kg/ha). Unlike nitrogen, readily available phosphorus is usually located in the topsoil layer (J. Lynch, 1995; J. P. Lynch & Brown, 2001). As a result, cover crop species with shallow root angles and relatively higher root biomass in the topsoil have been found to be efficient P scavengers. In like manner, Heuermann et al. (2019) classified the topsoil root biomass for Mix 1 and its components in Asendorf as Bristle oats > Mix 1 > Phacelia>Mustard > Clover.

Our results for phosphorus uptake show that Phacelia> Mix 1> Mustard> Clover> Oats. Despite a relatively high topsoil root biomass, Bristle oats had the least phosphorus uptake, and Phacelia outperforms Mix 1. While topsoil root biomass is important, it is not sufficient to uniquely explain P uptake as there are other physiological mechanisms involved in P uptake like P-mobilizing enzymes and the ability to establish symbiosis with mycorrhizae (Dakora & Phillips, 2002; Koshila Ravi & Muthukumar, 2024).

As with the case of N and P uptake, from Figure 4, it can also observed that the peak potassium (K) uptake from the cover crop treatments during the sampling period follows the descending order; Mix 3 (306.9 kg/ha) > Mix 4 (285.9 kg/ha) > Mix 6 (276.8 kg/ha) > Mix 2 (252 kg/ha) > Mix 5 (242.8 kg/ha) > Mix 7 (199.4 kg/ha) > Phacelia (162.9 kg/ha) > Mix 1 (142.6 kg/ha) > Clover (125.2 kg/ha) > Mustard (88.22 kg/ha) > Oats (74.17 kg/ha), showing a superior ability from Mixes to uptake K over single species of cover crops.

The peak macro nutrient uptake from each cover crop gives an indication of what could be potentially provided to the subsequent cash crop after biomass mineralization. This information can be also used in choosing and adjusting the subsequent cash crop fertilizer needs. DSV Seeds, the provider of the cover crops, recommends to plant Mix 2 before cereals or maize; Mix 3 before Cereals, oilseed rape, or Sugar beet; Mix 4 before oil seed rape, legumes, sugar beet, cereals or maize; Mix 5 before oil seed rape, cereals or Mais; Mix 6 before sugar beet or oil seed rape, and Mix 7 before legumes, cereals or maize. The composition and peak macro nutrient uptake from each of the Mixes also can provide the agronomic basis for choosing a specific mix in the rotation according to soil nutrient levels and risk of environmental losses.

As this is ongoing research work, validation results for the crop-specific model approach is only available for Mix 2 for which there was more data available. Figure 5 compares the measured macro nutrient uptake for Mix 2 with the corresponding sensor-predicted macro nutrient uptake during validation with a part of the collected data that was not used for calibration. Based on the $R^2$ values, from Figure 5, it can be inferred that the sensor vegetation index contains reasonably good information for the prediction of P, Mg, S and Ca uptake for Mix 2. For N the $R^2$ was lower, but the RMSE showed reliable information, on the other hand K showed values under requirements in this case. As the same methodology was used for the calibration of the other cover crops, we are confident that the sensor predictions from the other cover crops would be also plausible having enough calibration results. However, more data is required to get a clearer picture of the feasibility of predicting macro nutrient uptake from the other cover crops.

## Macro nutrient uptake prediction (generalized model approach)

Table 3 shows summaries of the RMSE and $R^2$ as a way of assessing the generalized model approach accuracy, where the combined data set was used to predict the macro nutrients uptake of one of the cover crops treatments.

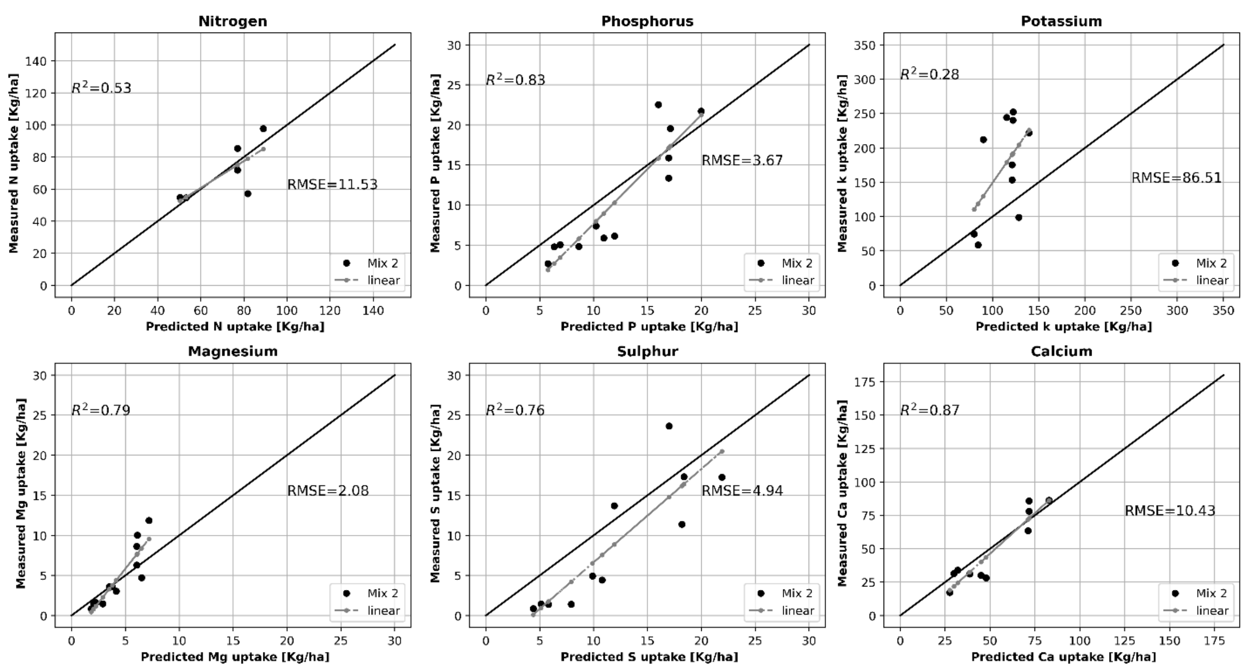


**Figure 5:Comparison of sensor-predicted and measured Macro nutrient uptake for Mix 2 validation.**

**Table 2: generalized model validation**

| Nutrient | N | | P | | K | | Ca | | Mg | | S | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cover Crop | $R^2$ | RMSE kg/ha | $R^2$ | RMSE kg/ha | $R^2$ | RMSE kg/ha | $R^2$ | RMSE kg/ha | $R^2$ | RMSE kg/ha | $R^2$ | RMSE kg/ha |
| Mix 1 | **0.68** | 10 | **0.74** | 3.2 | 0.29 | 32.3 | 0.57 | 16.2 | **0.67** | 1.0 | 0.53 | 3.2 |
| Mix 2 | **0.71** | 12 | **0.75** | 3.2 | 0.58 | 51.6 | **0.78** | 12.0 | **0.78** | 1.4 | **0.71** | 5.3 |
| Mix 3 | 0.41 | 32 | 0.54 | 5.5 | **0.68** | 61.7 | 0.45 | 27.5 | 0.34 | 4.6 | 0.48 | 3.7 |
| Mix 4 | **0.73** | 18 | **0.71** | 6.6 | **0.78** | 77.0 | **0.81** | 26.9 | **0.6** | 6.5 | **0.63** | 4.7 |
| Mix 5 | 0.53 | 17 | **0.86** | 5.7 | **0.95** | 42.8 | **0.77** | 14.3 | **0.83** | 1.6 | **0.72** | 7.5 |
| Mix 6 | **0.66** | 18 | **0.65** | 5.6 | **0.73** | 45.2 | **0.66** | 21.3 | 0.55 | 4.4 | **0.6** | 3.5 |
| Mix 7 | 0.16 | 21 | 0.19 | 7.8 | 0.27 | 50.4 | 0.15 | 20.2 | 0.14 | 3.5 | 0.21 | 10.9 |
| Clover | **0.85** | 23 | **0.75** | 9.7 | **0.85** | 95.2 | **0.86** | 41.8 | **0.79** | 5.2 | **0.86** | 6.0 |
| Mustard | **0.8** | 7 | **0.68** | 2.8 | **0.61** | 22.0 | **0.8** | 7.8 | **0.74** | 1.5 | 0.7 | 6.4 |
| Oats | **0.61** | 45 | 0.32 | 11.1 | 0.17 | 119.4 | 0.24 | 56.1 | 0.35 | 6.9 | 0.16 | 7.8 |
| Phacelia | **0.7** | 8 | **0.9** | 5.5 | 0.17 | 38.7 | **0.97** | 56.2 | **0.71** | 1.0 | **0.78** | 2.4 |
| **Average** | **0.62** | 19 | **0.64** | 6.1 | **0.55** | 57.8 | **0.64** | 27.3 | **0.59** | 3.4 | **0.58** | 5.6 |

On the generalized model approach (Table 3), values that present $R^2 \geq 0.6$ (bolted) are considered as cases where the vegetation index enables reasonably good prediction of a specific macro nutrient uptake from a specific cover crop. For instance, for Mix1; N, P, and Mg uptake can be predicted. While for Mix 2, N, P, Ca, Mg and S uptake can be estimated from the method. A more simplified result could be that despite Mix 3 (based on N fixing species and legumes), Mix 7 (heavily based on Brassica species), and Oats (single crops with narrow leaves different from the rest), those deserving individual calibrations. The remainder (Mix 1, Mix 2, Mix 4, Mix 5, Mix 6, Clover, Mustard and Phacelia) cover crops macronutrients uptake could be sensor-predicted with reasonable accuracy by the generalized model calibration. The RMSE (kg/ha) is also generally higher compared with the crop-specific approach.

## Conclusions

The results show that sensor-predicted macro-nutrient uptake for most of the cover crops correlates well with measured macro nutrients (N, P, K, Ca, Mg and S) uptake. A further increase in the number of cover crops samplings data could further improve results and backup the findings. This demonstrates that the amount of above-ground biomass and its macro nutrient content can be remotely predicted at the field scale using a vegetation sensor.

These results can be used on large scale by computing equivalent vegetation indices from satellite data. A logical next step for this research is to estimate the amount of macro-nutrient taken up that can be released to the subsequent cash crop seasons due to mineralization of the cover crop biomass. This would be very valuable information for a multi-season nutrient management plan at infield scale, as farmers can then precisely adjust their fertilizer application by considering the amount of macro nutrients that can be released through mineralization of the available cover crop biomass.


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