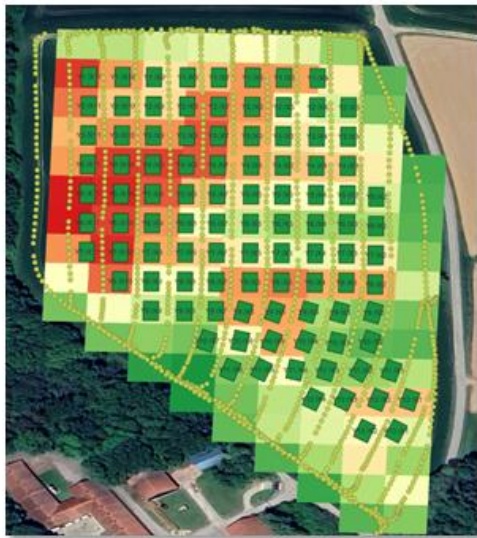


## Appendix 1: Mean temperature (°C) and precipitation (mm) at experimental sites

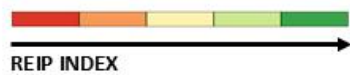
| Experimental site                              | unit | Jan–Mar | Apr–Jun | Jul–Sep | Oct–Dec | Year |
|------------------------------------------------|------|---------|---------|---------|---------|------|
| <b><u>Thalhausen (Site A)<sup>1</sup></u></b>  |      |         |         |         |         |      |
| Temperature $\bar{x}$ 1991–2020                | °C   | 1.4     | 13.0    | 16.4    | 4.3     | 8.8  |
| Temperature $\bar{x}$ 2019                     | °C   | 2.6     | 13.5    | 17.2    | 5.6     | 9.7  |
| Temperature $\bar{x}$ 2021                     | °C   | 1.9     | 11.9    | 16.3    | 4.3     | 8.6  |
| Temperature $\bar{x}$ 2023                     | °C   | 3.6     | 13.0    | 18.3    | 6.5     | 10.4 |
| Temperature $\bar{x}$ 2024                     | °C   | 4.9     | 14.0    | 18.0    | 5.3     | 10.6 |
| Precipitation $\Sigma$ 1991–2020               | mm   | 140     | 241     | 262     | 168     | 813  |
| Precipitation $\Sigma$ 2019                    | mm   | 173     | 209     | 201     | 141     | 724  |
| Precipitation $\Sigma$ 2021                    | mm   | 130     | 321     | 317     | 145     | 914  |
| Precipitation $\Sigma$ 2023                    | mm   | 68.1    | 214     | 338     | 276     | 899  |
| Precipitation $\Sigma$ 2024                    | mm   | 146     | 366     | 433     | 111     | 1057 |
| <b><u>Roggenstein (Site B)<sup>1</sup></u></b> |      |         |         |         |         |      |
| Temperature $\bar{x}$ 1991–2020                | °C   | 1.6     | 12.8    | 16.5    | 4.5     | 8.9  |
| Temperature $\bar{x}$ 2022                     | °C   | 3.2     | 13.6    | 17.2    | 6.6     | 10.2 |
| Precipitation $\Sigma$ 1991–2020               | mm   | 157     | 267     | 284     | 180     | 888  |
| Precipitation $\Sigma$ 2022                    | mm   | 67      | 225     | 213     | 185     | 692  |
| <b><u>Burghausen (Site C)<sup>2</sup></u></b>  |      |         |         |         |         |      |
| Temperature $\bar{x}$ 1991–2020                | °C   | 1.3     | 13.2    | 16.7    | 4.2     | 8.9  |
| Temperature $\bar{x}$ 2020                     | °C   | 3.5     | 13.5    | 17.6    | 4.6     | 9.8  |
| Precipitation $\Sigma$ 1991–2020               | mm   | 150     | 243     | 285     | 167     | 848  |
| Precipitation $\Sigma$ 2020                    | mm   | 154     | 276     | 303     | 129     | 863  |

<sup>1</sup> Algorithm derivation for N uptake estimation, <sup>2</sup> Practical implementations of site-specific N uptake, N balancing and nitrate leaching modeling

**Appendix 2: Example of a Field in Site A at BBCH 65 (flowering), showing the satellite-derived REIP (20 × 20 m grid) and corresponding harvested plot locations used for model calibration.**



Satellite-derived REIP (20 × 20 m grid)



Experimental plots harvested with plot combine harvester

### Appendix 3: Equations used by the soil-water-nitrate leaching model

$$N_{surplus\_l} = N_{Min\_Pool} + N_{Min\_SON} + N_{Dep} + N_{MF} + N_{Min\_OF} - \Delta SON - N_{NH_3L} - N_{DL(act)} - N_Y \quad (1)$$

$$N_{DL(act)} = N_{DL(max)} \cdot c(N) \cdot (k + c(N))^{-1} \quad (1.1)$$

$$N_{Min\_SON} = N_{SON\_start} \cdot N_{Min\_SON\_share(max)} + \sum_{i=1}^n N_{SON\_OF,i} N_{Min\_SON\_share(act),i} \quad (1.2)$$

$$N_{SON\_OF} = (N_{OF} - N_{OF\_NH_4-N}) - (FR_{OF,DM} \cdot h \cdot 50) \quad (1.2.1)$$

$$\begin{aligned} N_{Min\_SON\_share(act)} &= N_{Min\_SON\_share(max)} \cdot (0.22679 + 0.1633427 d + 1.7458 \cdot 10^{-4} d^2 + 2.21979 \\ &\quad \cdot 10^{-6} d^3 + 1.41236 \cdot 10^{-11} d^5) \end{aligned} \quad (1.2.2)$$

$$N_{Min\_SON\_share(max)} = \begin{cases} 10 & \text{if } BAT \leq 10 \\ 10 + 0.75(BAT - 10) & \text{if } 10 < BAT < 50 \\ 40 & \text{if } BAT \geq 50 \end{cases} \quad (1.2.3)$$

$$BAT = P0(soil\_texture) + P1(soil\_texture) \cdot Temp + P2(soil\_texture) \cdot Prec \quad (1.2.4)$$

$$L_{NO_3-conc} = N_{surplus\_l} \cdot LR^{-1} \cdot LF \cdot 443 \quad (2)$$

$$LR = 0.92 Prec_{bGP} + 0.61 Prec_{GP} - 153 \cdot (\log W_{PaW}) - 0.12 ETP + 109 \quad (2.1)$$

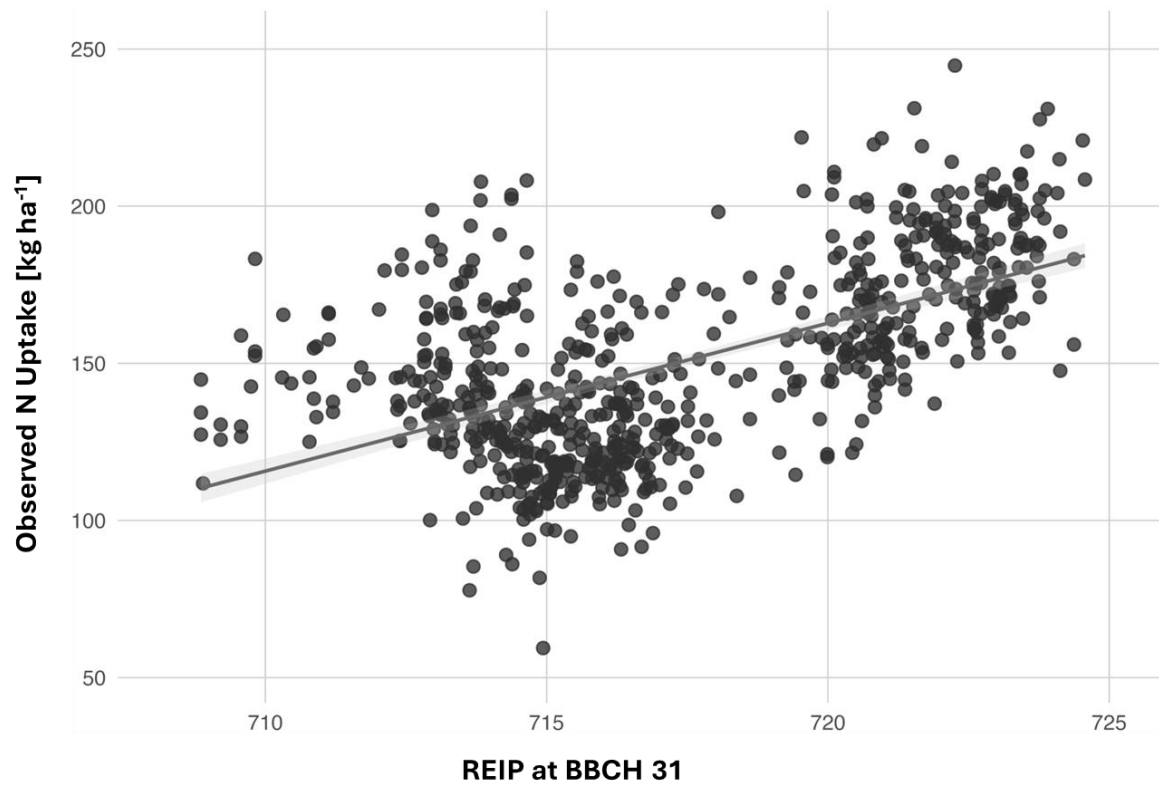
$$ETP = (RG + 90) \cdot (Temp + 22) \cdot (150 \cdot (Temp + 123))^{-1} \quad (2.2)$$

$$LF = LR \cdot FC^{-1} \quad (2.3)$$

$$N_{NO_3-L} = L_{NO_3-conc} \cdot \frac{1}{443} \cdot LR \quad (3)$$

| Symbol                            | Parameter                                                                                                                                                 | Scale unit                           |
|-----------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------|
| $N_{\text{surplus}_l}$            | N surplus of leachable N                                                                                                                                  | kg ha <sup>-1</sup>                  |
| $N_{\text{Min\_Pool}}$            | Mineral N pool at simulation start                                                                                                                        | kg ha <sup>-1</sup>                  |
| $N_{\text{Min\_SON}}$             | Mineralization of the mineralizable organic N pool                                                                                                        | kg ha <sup>-1</sup>                  |
| $N_{\text{Dep}}$                  | N deposition                                                                                                                                              | kg ha <sup>-1</sup> yr <sup>-1</sup> |
| $N_{\text{MF}}$                   | N from mineral fertilizers                                                                                                                                | kg ha <sup>-1</sup>                  |
| $N_{\text{Min\_OF}}$              | Mineral N from organic fertilizers                                                                                                                        | kg ha <sup>-1</sup>                  |
| $\Delta\text{SON}$                | Changes in soil organic N stocks in the humus N pool according to Hülsbergen (2003), Küstermann et al. (2008), Leithold et al. (2015)                     | kg ha <sup>-1</sup>                  |
| $N_{\text{NH}_3\text{L}}$         | Ammonia losses from fertilizer application according to Abraham (2001)                                                                                    | kg ha <sup>-1</sup>                  |
| $N_{\text{DL(act)}}$              | Actual denitrification losses according to Hermsmeyer and van der Ploeg (1996a)                                                                           | kg ha <sup>-1</sup>                  |
| $N_Y$                             | Crop N uptake in main-products and by-products                                                                                                            | kg ha <sup>-1</sup>                  |
| $N_{\text{DL(max)}}$              | Maximum denitrification potential according to Köhne and Wendland (1992)                                                                                  | kg ha <sup>-1</sup>                  |
| $c(\text{N})$                     | Mean N concentration subject to denitrification in the 0–50 cm soil layer during the observation period according to Hermsmeyer and van der Ploeg (1996b) | mg kg <sup>-1</sup> soil             |
| $k$                               | Constant according to Köhne and Wendland (1992)                                                                                                           | NO <sub>3</sub> -N kg <sup>-1</sup>  |
| $N_{\text{SON\_start}}$           | Mineralizable organic N pool at simulation start                                                                                                          | kg ha <sup>-1</sup>                  |
| $N_{\text{Min\_SON\_share(max)}}$ | Maximum share of N mineralization from the mineralizable organic N pool according to Abraham (2001)                                                       |                                      |
| $N_{\text{SON\_OF}}$              | Amount of applied mineralizable organic N                                                                                                                 | kg ha <sup>-1</sup>                  |
| $N_{\text{Min\_SON\_share(act)}}$ | Actual share of N mineralization from the mineralizable organic N pool according to Abraham (2001) and Franko et al. 1995                                 |                                      |
| $N_{\text{OF}}$                   | Total N applied with organic fertilizers                                                                                                                  | kg ha <sup>-1</sup>                  |
| $N_{\text{OF\_NH}_4\text{-N}}$    | Amount of ammonia N applied with organic fertilizers                                                                                                      | kg ha <sup>-1</sup>                  |
| $\text{FR}_{\text{OF,DM}}$        | Organic fertilizer application rate (dry matter amount)                                                                                                   | Mg ha <sup>-1</sup>                  |
| $h$                               | Fertilizer specific humufication coefficient according to Hülsbergen (2003), Küstermann et al. (2008), Leithold et al. (2015)                             | HU Mg <sup>-1</sup>                  |
| $d$                               | Day in year                                                                                                                                               |                                      |
| BAT                               | Biological active time according to Franko et al. 1995                                                                                                    |                                      |
| P0, P1, P2                        | Parameters according to Franko et al. 1995                                                                                                                |                                      |
| Temp                              | Mean annual temperature                                                                                                                                   | °C                                   |
| Prec                              | Total annual precipitation                                                                                                                                | mm                                   |
| $L_{\text{NO}_3\text{-conc}}$     | Leachate NO <sub>3</sub> -concentration                                                                                                                   | mg NO <sub>3</sub> l <sup>-1</sup>   |
| LR                                | Leachate rate according to Renger and Strebel (1980)                                                                                                      | mm yr <sup>-1</sup>                  |
| LF                                | Leachate factor                                                                                                                                           |                                      |
| $\text{Prec}_{\text{bGP}}$        | Precipitation beyond plant growth                                                                                                                         | mm                                   |
| $\text{Prec}_{\text{GP}}$         | Precipitation during plant growth                                                                                                                         | mm                                   |
| $W_{\text{PaW}}$                  | Plant available soil water at the effective rooting depth                                                                                                 | mm                                   |
| ETP                               | Evapotranspiration according to Wendling (1993)                                                                                                           | mm                                   |
| RG                                | Global radiation                                                                                                                                          | J cm <sup>-2</sup>                   |
| FC                                | Field capacity at the effective rooting depth                                                                                                             | mm                                   |
| $N_{\text{NO}_3\text{-L}}$        | Potential N loss due to nitrate leaching                                                                                                                  | kg ha <sup>-1</sup>                  |

**Appendix 4: Relationship between REIP and observed grain N uptake at harvest ( $\text{kg ha}^{-1}$ ) at BBCH stage 31 (n = 708)**



**Appendix 5: Correlation between REIP indices and observed grain N uptake (n = 708)**

| Index            | r    |
|------------------|------|
| REIP 1 (BBCH 31) | 0.56 |
| REIP 2 (BBCH 55) | 0.18 |
| REIP 3 (BBCH 65) | 0.39 |

-

**Appendix 6: Predictor variables used for grain N uptake modeling and retained variables after backward elimination**

| <b>Category</b>        | <b>Predictor variables initially used</b> | <b>Retained after backward elimination</b> | <b>Eliminated</b>                        |
|------------------------|-------------------------------------------|--------------------------------------------|------------------------------------------|
| Spatial/topographic    | X, Y, Height, Hight relative              | X, Height relative                         | Y, Height                                |
| Soil                   | Ackerzahl, Bodenzahl                      | Ackerzahl, Bodenzahl                       | –                                        |
| Satellite-based        | REIP_1, REIP_2, REIP_3                    | REIP_2, REIP_3                             | REIP_1                                   |
| Climate: temperature   | JanT, FebT, MrzT, AprT, MaiT, JunT, JulT  | JanT, FebT, MrzT                           | AprT, MaiT, JunT, JulT                   |
| Climate: precipitation | JanN, FebN, MrzN, AprN, MaiN, JunN, JulN  | –                                          | JanN, FebN, MrzN, AprN, MaiN, JunN, JulN |
| Temporal               | Year                                      | Year                                       | –                                        |