**Supplementary material**

**Explanation of the relief parameters (without elevation, slope and aspect):**

Upslope catchment area (CA) [m2]:

This parameter indicates the uphill catchment area.

Topographical wetness index (TWI) [−]:

Higher TWI values represent drainage depressions, lower values represent crests and ridges.

TWI = ln(*a*/tan B)

a = Upstream contributing area in m2; B = Slope

Plancurvature (PLC) [−]:

Perpendicular to the direction of the maximum slope. A positive value indicates the surface is sidewardly convex at that cell. A negative plan indicates the surface is sidewardly concave at that cell. A value of zero indicates the surface is linear.

Profilecurvature (PRC) [−]: ;

Profile curvature is parallel to the direction of the maximum slope. A negative value indicates that the surface is upwardly convex at that cell. A positive profile indicates that the surface is upwardly concave at that cell. A value of zero indicates that the surface is linear. Profile curvature affects the acceleration or deceleration of flow across the surface.

Convergence (CON) [%]:

Calculates an index of convergence/divergence regarding to overland flow. By its meaning it is similar to plan or horizontal curvature, but gives much smoother results. The calculation uses the aspects of surrounding cells, i.e. it looks to which degree surrounding cells point to the center cell. The result is given as percentages, negative values correspond to convergent, positive to divergent flow conditions. Minus 100 would be like a peak of a cone, plus 100 a pit, and 0 an even slope.

LS-factor (LSF) [−]

The Universal Soil Loss Equation (USLE) model is the most frequently used model for soil erosion risk estimation. Among the six input layers, the combined slope length and slope angle. The S-factor measures the effect of slope steepness, and the L-factor defines the impact of slope length. The combined LS-factor describes the effect of topography on soil erosion.

Channel network base level (CNBL) [−]:

This parameter describes the stream network in combination with the channel direction.

Vertical distance to channel network (VDCN) [−]:

This tool calculates the vertical distance to a channel network base level. The algorithm consists of two major steps:

1. Interpolation of a channel network base level elevation

2. Subtraction of this base level from the original elevations

Valley depth (VD) [m]

Valley depth is calculated as difference between the elevation and an interpolated ridge level. Ridge level interpolation uses the algorithm implemented in the 'Vertical Distance to Channel Network' tool. It performs the following steps:

- Definition of ridge cells (using Strahler order on the inverted DEM).

- Interpolation of the ridge level.

- Subtraction of the original elevations from the ridge level.

Relative slope position (RSP) [−]:

Values are normalized with a range from 0 to 1;

RSP = [vertical distance to channel network] / ( [vertical distance to channel network] / [Valley Depth] )

**Supplementary Table 1.** Simulation of the yield of the control plots (means of the years 1981–2013) with REG (above: predictors ECa , relief, coordinate, below; predictors ECa ).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Target variable | Year | Predictors | Regression coefficients | Sig. | Standard beta-coeff. | Adj. R² sign. | RMSD |
| Yield  (dt ha-1] | Mean of the years 1981–2013 | Constant | 8.773 | 0.064 |  | 0.831\*\*\* | 1.26 |
| ECa MK2-h-0.5 (1/x) | 514.653 | 0.005 | 0.551 |
| Catchment area (1/x) | –402.907 | 0.007 | -0.508 |
| Yield (dt ha-1) | Mean of the years 1981–2013 | Constant | 42.173 | 0.000 |  | 0.704\*\*\* | 1.45 |
| ECa MK2-h-0.5 | –0.576 | 0.000 | 0.991 |

**Supplementary Table 2.** Modeling of the yield (means of the years 1981–2013) with ANOVA with the factors fertilization level and fertilizer number.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Target  Variable | Year | Model and effects | Regression coefficients | Sig. | Partial eta-quadrat | Adj. R2 | RMSD |
| Yield  [dt ha-1] | Mean of the years 1981–2013 | Adjusted model | 2.991 | 0.003 | 0.314 | 0.209 | 5.23 |
| Constant | 8328.984 | 0.000 | 0.991 |
| Fertilizer no. | 2.281 | 0.055 | 0.137 |
| Fertilization level | 19.911 | 0.000 | 0.217 |
| Fertilization level\*Fertilizer no. | 0.093 | 0.993 | 0.006 |

**Supplementary Table 3.** Modeling of the yield (means of the years 1981–2013) with ANCOVA with the factors fertilization level and fertilizer number and the covariates ECa, topographic parameters, and coordinates.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Target  Variable | Year | Model and effects | Regression coefficients | Sig. | Partial beta-quadrat | Adj. R2 | RMSD |
| Yield  [dt ha-1) | Means of the years 1981–2013 | Adjusted model | 38.565 | 0.000 | 0.897 | 0.845 | 2.30 |
| Constant | 1042.575 | 0.000 | 0.936 |
| ECa MK2-h-0.5 (√) | 295.372 | 0.000 | 0.806 |
| Fertilizer no. | 11.279 | 0.000 | 0.443 |
| Fertilization level | 138.846 | 0.000 | 0.662 |
| Fertilization level\*Fertilizer no. | 0.307 | 0.907 | 0.021 |

**Supplementary Table 4.** Simulation of the annual yield from 1981–2013 with REG of the control plots and the independent variables ECa, relief, and coordinates.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Year | Target variable | Predictors | Regression coefficients | Sig. | Standard beta-coeff. | Adj. R² sign. | RMSD |
| 1981 | Yield  20.22  dt ha-1 | Constant | 22563758.36 | 0.001 |  | 0.631\*\* | 1.41 |
| Y-GK (log) | –3353018.599 | 0.001 | –1.062 |
| ECa MK2-h-0.5 (ln) | 17.429 | 0.018 | 0.670 |
| 1984 | Yield  17.68  dt ha-1 | Constant | 5.436 | 0.026 |  | 0.883\*\*\* | 0.96 |
| Catchment area (√) | 0.307 | 0.000 | 0.875 |
| Profilecurvature (log) | –0.586 | 0.008 | –0.354 |
| 1987 | Yield  19.38  dt ha-1 | Constant | 800.549 | 0.000 |  | 0.959\*\*\* | 0.75 |
| Channel network base level (x³) | –7.49E-06 | 0.000 | –0.904 |
| Convergence (1/x) | 0.032 | 0.009 | 0.214 |
| Relative slope position (x³) | 4073711.289 | 0.020 | 0.176 |
| 1999 | Yield  21.21  dt ha-1 | Constant | 8.162 | 0.036 |  | 0.907\*\*\* | 0.95 |
| ECa MK2-v-1.0 (1/x) | 871.368 | 0.000 | 0.972 |
| Plancurvature  (log) | 0.681 | 0.017 | 0.274 |
| 1993 | Yield  17.42  dt ha-1 | Constant | 18.375 | 0.000 |  | 0.854\*\*\* | 1.36 |
| Slope gradient | –169.654 | 0.000 | –0.835 |
| Profilecurvature (log) | –0.717 | 0.020 | –0.328 |
| 1996 | Yield  24.45  dt ha-1 | Constant | 6.322 | 0.022 |  | 0.849\*\*\* | 1.43 |
| ECa MK2-h-1.0 (1/x) | 580.905 | 0.000 | 0.929 |
| 1999 | Yield  10.60  dt ha-1 | Constant | 16.86 | 0.000 |  | 0.778\*\*\* | 1.58 |
| ECa MK2-h-0.5 (x³) | –0.000116 | 0.000 | –0.893 |
| 2002 | Yield  33.44  dt ha-1 | Constant | 2514118.356 | 0.001 |  | 0.879\*\*\* | 2.87 |
| ECa MK2-h-0.5 (x²) | –0.024 | 0.000 | –1.173 |
| X-GK (√) | –1188.150 | 0.001 | –0.671 |
| 2008 | Yield  32.24  dt ha-1 | Constant | 4908.334 | 0.000 |  | 0.929\*\*\* | 1.51 |
| Channel network base level (1/x) | –2293318.335 | 0.000 | –0.970 |
| 2011 | Yield  21.75  dt ha-1 | Constant | –9853166.954 | 0.000 |  | 0.868\*\*\* | 0.50 |
| X-GK (log) | 1481458.337 | 0.000 | 0.942 |
| 2013 | Yield  20.81  dt ha-1 | Constant | 72.853 | 0.000 |  | 0.979\*\*\* | 0.76 |
| ECa MK2-v-1.0 (1/x) | –1860.501 | 0.000 | –1.082 |
| Profilecurvature (x²) | –69326.894 | 0.009 | –0.308 |

**Supplementary Table 5a.** Simulation of the annual yield from 1981–2013 with ANOVA with the factors fertilization level and fertilizer number.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Year | Target variable | Model and effects | Regression coefficients | Sig. | Partial eta-quadrat | Adj. R2 | RMSD |
| 1981 | Yield  dt ha-1 | Adjusted model | 5.227 | 0.000 | 0.444 | 0.359 | 4.03 |
| Constant | 8036.706 | 0.000 | 0.991 |
| Fertilizer no. | 2.179 | 0.066 | 0.131 |
| Fertilization level | 40.866 | 0.000 | 0.362 |
| Fertilization level\*Fertilizer no. | 0.239 | 0.944 | 0.016 |
| 1984 | Yield  dt ha-1 | Adjusted model | 10.054 | 0.000 | 0.606 | 0.545 | 3.73 |
| Constant | 13676.192 | 0.000 | 0.995 |
| Fertilizer no. | 12.399 | 0.000 | 0.463 |
| Fertilization level | 42.89 | 0.000 | 0.373 |
| Fertilization level\*Fertilizer no. | 1.137 | 0.349 | 0.073 |
| 1987 | Yield  dt ha-1 | Adjusted model | 4.743 | 0.000 | 0.420 | 0.332 | 2.59 |
| Constant | 22327.806 | 0.000 | 0.997 |
| Fertilizer no. | 4.174 | 0.002 | 0.225 |
| Fertilization level | 0.878 | 0.352 | 0.012 |
| Fertilization level\*Fertilizer no. | 5.735 | 0.000 | 0.285 |
| 1990 | Yield  dt ha-1 | Adjusted model | 9.102 | 0.000 | 0.582 | 0.518 | 3.83 |
| Constant | 21152.869 | 0.000 | 0.997 |
| Fertilizer no. | 7.631 | 0.000 | 0.346 |
| Fertilization level | 52.446 | 0.000 | 0.421 |
| Fertilization level\*Fertilizer no. | 1.671 | 0.153 | 0.104 |
| 1993 | Yield  dt ha-1 | Adjusted model | 7.288 | 0.000 | 0.527 | 0.455 | 4.18 |
| Constant | 7880.268 | 0.000 | 0.991 |
| Fertilizer no. | 7.744 | 0.000 | 0.350 |
| Fertilization level | 35.067 | 0.000 | 0.328 |
| Fertilization level\*Fertilizer no. | 0.532 | 0.752 | 0.036 |
| 1996 | Yield  dt ha-1 | Adjusted model | 13.807 | 0.000 | 0.678 | 0.629 | 2.54 |
| Constant | 37630.859 | 0.000 | 0.998 |
| Fertilizer no. | 8.782 | 0.000 | 0.379 |
| Fertilization level | 102.37 | 0.000 | 0.587 |
| Fertilization level\*Fertilizer no. | 1.402 | 0.234 | 0.089 |
| 1999 | Yield  dt ha-1 | Adjusted model | 3.111 | 0.002 | 0.322 | 0.219 | 5.96 |
| Constant | 3744.367 | 0.000 | 0.981 |
| Fertilizer no. | 5.060 | 0.000 | 0.260 |
| Fertilization level | 7.215 | 0.009 | 0.091 |
| Fertilization level\*Fertilizer no. | 0.171 | 0.972 | 0.012 |
| 2002 | Yield  dt ha-1 | Adjusted model | 2.331 | 0.017 | 0.271 | 0.155 | 6.08 |
| Constant | 9231.990 | 0.000 | 0.993 |
| Fertilizer no. | 1.691 | 0.148 | 0.109 |
| Fertilization level | 14.429 | 0.000 | 0.173 |
| Fertilization level\*Fertilizer no. | 0.481 | 0.789 | 0.034 |
| 2008 | Yield  dt ha-1 | Adjusted model | 19.141 | 0.000 | 0.830 | 0.787 | 1,77 |
| Constant | 71164.320 | 0.000 | 0.999 |
| Fertilizer no. | 19.878 | 0.000 | 0.698 |
| Fertilization level | 69.506 | 0.000 | 0.618 |
| Fertilization level\*Fertilizer no. | 5.209 | 0.001 | 0.377 |
| 2011 | Yield  dt ha-1 | Adjusted model | 8.272 | 0.000 | 0.679 | 0.597 | 4.57 |
| Constant | 12755.795 | 0.000 | 0.997 |
| Fertilizer no. | 11.940 | 0.000 | 0.581 |
| Fertilization level | 24.895 | 0.000 | 0.367 |
| Fertilization level\*Fertilizer no. | 0.536 | 0.748 | 0.059 |
| 2013 | Yield  dt ha-1 | Adjusted model | 6.939 | 0.000 | 0.640 | 0.547 | 6.90 |
| Constant | 4727.024 | 0.000 | 0.991 |
| Fertilizer no. | 8.871 | 0.000 | 0.508 |
| Fertilization level | 25.497 | 0.000 | 0.372 |
| Fertilization level\*Fertilizer no. | 0.436 | 0.821 | 0.048 |

**Supplementary Table 5b.** Simulation of the annual yield from 1981–2013 with ANCOVA with the factors fertilization level and fertilizer number and the covariates ECa, relief parameters, and coordinates.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Year | Target variable | Model and effects | Regression coefficients | Sig. | Partial eta-quadrat | Adj. R2 | RMSD |
| 1981 | Yield  dt ha-1 | Adjusted model | 6.238 | 0.000 | 0.537 | 0.451 | 3.68 |
| Constant | 116.632 | 0.000 | 0.625 |
| Plancurvat (log) | 10.785 | 0.002 | 0.134 |
| Profilcuvature (log) | 4.808 | 0.032 | 0.064 |
| Fertilizer no. | 2.059 | 0.081 | 0.128 |
| Fertilization level | 45.251 | 0.000 | 0.393 |
| Fertilization level\*Fertilizer no. | 0.527 | 0.755 | 0.036 |
| 1984 | Yield  dt ha-1 | Adjusted model | 10.054 | 0.000 | 0.606 | 0.545 | 3.73 |
| Constant | 13676.192 | 0.000 | 0.995 |
| Fertilizer no. | 200.954 | 0.000 | 0.463 |
| Fertilization level | 695.162 | 0.000 | 0.373 |
| Fertilization level\*Fertilizer no. | 18.432 | 0.349 | 0.073 |
| 1987 | Yield  dt ha-1 | Adjusted model | 5.554 | 0.000 | 0.508 | 0.416 | 2.39 |
| Constant | 12334.778 | 0.000 | 0.994 |
| LS - Faktor (x³) | 7.309 | 0.009 | 0.095 |
| Convergence (1/x) | 4.448 | 0.039 | 0.06 |
| Fertilizer no. | 4.779 | 0.001 | 0.254 |
| Fertilization level | 0.887 | 0.350 | 0.013 |
| Fertilization level\*Fertilizer no. | 6.623 | 0.000 | 0.321 |
| 1990 | Yield  dt ha-1 | Adjusted model | 29.242 | 0.000 | 0.832 | 0.803 | 2.43 |
| Constant | 5786.464 | 0.000 | 0.988 |
| ECa MK2-h-0.5 (x²) | 105.482 | 0.000 | 0.598 |
| Fertilizer no. | 17.328 | 0.000 | 0.55 |
| Fertilization level | 151.62 | 0.000 | 0.681 |
| Fertilization level\*Fertilizer no. | 4.132 | 0.002 | 0.225 |
| 1993 | Yield  dt ha-1 | Adjusted model | 34.120 | 0.000 | 0.864 | 0.838 | 2.25 |
| Constant | 75.849 | 0.000 | 0.520 |
| Höhe (x³) | 3.145 | 0.081 | 0.043 |
| Slope gradient (x³) | 65.149 | 0.000 | 0.482 |
| Fertilizer no. | 25.274 | 0.000 | 0.644 |
| Fertilization level | 153.216 | 0.000 | 0.686 |
| Fertilization level\*Fertilizer no. | 1.718 | 0.412 | 0.109 |
| 1996 | Yield  dt ha-1 | Adjusted model | 20.801 | 0.000 | 0.779 | 0.741 | 2.11 |
| Constant | 12052.102 | 0.000 | 0.994 |
| Slope gradient (x²) | 32.108 | 0.000 | 0.311 |
| Fertilizer no. | 10.765 | 0.000 | 0.421 |
| Fertilization level | 156.676 | 0.000 | 0.688 |
| Fertilization level\*Fertilizer no. | 1.929 | 0.100 | 0.12 |
| 1999 | Yield  dt ha-1 | Adjusted model | 51.266 | 0.000 | 0.897 | 0.879 | 2.33 |
| Constant | 8580.125 | 0.000 | 0.992 |
| ECa MK2-h1.0 (x³) | 394.122 | 0.000 | 0.847 |
| Fertilizer no. | 32.029 | 0.000 | 0.693 |
| Fertilization level | 75.789 | 0.000 | 0.516 |
| Fertilization level\*Fertilizer no. | 1.134 | 0.350 | 0.074 |
| 2002 | Yield  dt ha-1 | Adjusted model | 27.344 | 0.000 | 0.841 | 0.811 | 2.83 |
| Constant | 398.357 | 0.000 | 0.856 |
| ECa MK2-h-0.5 (ln) | 113.731 | 0.009 | 0.629 |
| Aspect (x³) | 15.74 | 0.039 | 0.19 |
| Fertilizer no. | 10.016 | 0.001 | 0.428 |
| Fertilization level | 84.133 | 0.000 | 0.557 |
| Fertilization level\*Fertilizer no. | 2.581 | 0.034 | 0.162 |
| 2008 | Yield  dt ha-1 | Adjusted model | 21.298 | 0.000 | 0.882 | 0.84 | 1.48 |
| Constant | 864.147 | 0.000 | 0.956 |
| Plancurvature(x²) | 9.317 | 0.004 | 0.189 |
| Profilcuvature (x³) | 6.4 | 0.015 | 0.138 |
| relative slope position (RSP) (log) | 4.071 | 0.050 | 0.092 |
| Fertilizer no. | 13.016 | 0.000 | 0.619 |
| Fertilization level | 0.19 | 0.666 | 0.005 |
| Fertilization level\*Fertilizer no. | 5.465 | 0.001 | 0.406 |
| 2011 | Yield  dt ha-1 | Adjusted model | 32.395 | 0.000 | 0.911 | 0.883 | 2.32 |
| Constant | 397.306 | 0.000 | 0.906 |
| ECa MK2-h-0.5 (x³) | 83.32 | 0.000 | 0.670 |
| Valley depth(x³) | 15.11 | 0.000 | 0.269 |
| Fertilizer no. | 33.236 | 0.000 | 0.802 |
| Fertilization level | 105.64 | 0.000 | 0.720 |
| Fertilization level\*Fertilizer no. | 2.836 | 0.027 | 0.257 |
| 2013 | Yield  dt ha-1 | Adjusted model | 13.717 | 0.000 | 0.828 | 0.767 | 4,77 |
| Constant | 4.311 | 0.044 | 0.097 |
| ECa MK2-h-0.5 (x³) | 38.05 | 0.000 | 0.488 |
| Valley depth(1/x) | 25.129 | 0.000 | 0.386 |
| Slope gradient (x³) | 12.293 | 0.001 | 0.235 |
| Fertilizer no. | 8.904 | 0.000 | 0.527 |
| Fertilization level | 58.031 | 0.000 | 0.592 |
| Fertilization level\*Fertilizer no. | 0.337 | 0.888 | 0.040 |