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## Effects of straw mulch on soil nitrate dynamics, weeds, yield and soil erosion in organically grown potatoes

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### Abstract

The application of straw mulch to organic seed potatoes (*Solanum tuberosum* L.) has been shown to reduce virus incidence. In order to determine the associated agronomic effects of straw mulch, applied at 2.5–5 t ha<sup>-1</sup>, on soil nitrate dynamics, weed development, tuber yield and soil erosion, 12 field experiments were evaluated. Experiments were conducted on organic farms over 3 years at two locations in a temperate climate (635–709 mm precipitation/year; 8.1 °C mean air temperature) on loamy silt soils. Tuber yield and tuber size distribution were not influenced significantly by mulching. However, the risk of undesirable post harvest N-leaching was significantly reduced due to the immobilization of nitrate-N after harvest at 6.8–7.0 kg N t<sup>-1</sup> straw in two experiments (18–34 kg NO<sub>3</sub>-N ha<sup>-1</sup>). There was no consistent effect of straw mulch on number of weeds, weed cover and above ground biomass of weeds. The fact that yield and weed development were not significantly affected by straw mulch is mainly attributed to the relatively low amounts of straw applied. Soil erosion was reduced by >97% in a rain simulation experiment on a potato field of 8% slope with 20% crop cover. Soil loss was greatest (1606 g m<sup>-2</sup>) in the unmulched treatment, and 31, 42 and 26 g m<sup>-2</sup> in treatments with chopped straw at 1.25, 2.5 and 5 t ha<sup>-1</sup>, respectively.

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**Keywords:** Straw mulch; Nitrogen; Organic farming; Potato; Soil erosion; Weeds

### 1. Introduction

Straw mulch applications have been reported to reduce virus diseases in various crops such as barley

(Kendall et al., 1991), lupins (Jones, 1994) and rape (Heimbach and Eggers, 2002). This has led to the experimental transfer of this approach to seed potatoes (Heimbach et al., 2002; Saucke and Döring, 2004), where tuber transmitted viruses are still a severe problem (Stevenson, 2001).

Mulching with cereal straw was a frequent practice in potato growing several decades ago in parts of

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38 North America (Albrecht, 1922; Rowe-Dutton, 1957),  
39 and it was recognized that straw mulch might be useful  
40 against “degeneration”, i.e., for virus control in seed  
41 potatoes (Werner, 1929; also see Emerson, 1907); but  
42 straw mulching in potatoes disappeared from com-  
43 mercial practice when its function to increase soil  
44 moisture (Russel, 1940; Verma and Kohnke, 1951)  
45 was taken over by sprinkler irrigation (Pavlista, 2004,  
46 University of Nebraska, personal communication),  
47 and weed suppression (Rowe-Dutton, 1957) was  
48 achieved by the use of herbicides. With this shift,  
49 however, associated beneficial effects of straw mulch  
50 were also lost, one of the most important being the  
51 reduction of soil erosion (Duley and Kelly, 1939; Borst  
52 and Woodburn, 1942a; Dawson, 1946; Adams, 1966;  
53 Edwards et al., 2000).

54 Effects of straw mulch on tuber yield, however,  
55 have been variable, and this was mainly attributed to  
56 differences in climatic conditions. While yield  
57 increase through straw mulch was frequently found  
58 under hot and dry summer conditions (Bushnell and  
59 Welton, 1931; Singh et al., 1987), reduced yields  
60 under straw mulch have also been reported and were  
61 attributed to below-optimum soil temperature (Opitz,  
62 1948; Jacks et al., 1955; Rowe-Dutton, 1957), reduced  
63 soil nitrate levels (Scott, 1921; Albrecht, 1922;  
64 Albrecht and Uhlend, 1925) and mulching too early  
65 (Bushnell and Welton, 1931).

66 Increasing the quantity of mulch applied increases  
67 the effects on soil moisture and temperature (Scott,  
68 1921; Russel, 1940); therefore, large application rates  
69 ( $10 \text{ t ha}^{-1}$  and more), which were common in past  
70 studies and practice, appear to increase the risk of  
71 yield reduction in cooler climates. In contrast, the  
72 benefits of straw mulch on soil erosion and virus  
73 control are obtained at considerably lower levels. Even  
74 quantities of  $1.5\text{--}2.5 \text{ t ha}^{-1}$  of straw, that leave part of  
75 the soil uncovered, were found to check erosion to a  
76 large extent (80% and more; Borst and Woodburn,  
77 1942b; Lal, 1987; Nill and Nill, 1993). Regarding  
78 virus control, small to moderate amounts of straw (at  
79  $3.5\text{--}5 \text{ t ha}^{-1}$ ) have been shown to consistently reduce  
80 aphid infestation and potato virus Y (PVY) incidence  
81 in potatoes (Saucke and Döring, 2004).

82 To make use of these benefits under temperate  
83 climatic conditions, where soil moisture in summer is  
84 rarely limiting potato growth, it therefore appears to be  
85 reasonable to apply only small to moderate amounts of

86 straw, thereby avoiding the risk of reduced yields in  
87 cool and wet growing seasons. In order to evaluate this  
88 approach, the yield response to mulching with straw  
89 applied at  $2.5\text{--}5 \text{ t ha}^{-1}$  was quantified in 11 field  
90 experiments that were conducted over 3 years at two  
91 locations in Germany. An additional field experiment  
92 was set up on-farm in order to quantify effects of small  
93 to moderate amounts of straw mulch on soil erosion  
94 under conditions of organic potato growing.

95 A further pronounced effect of straw mulch  
96 application is the temporary immobilization of soil  
97 nitrogen (N) after straw incorporation into the soil due  
98 to the high C/N-ratio of straw (Cheshire et al., 1999).  
99 Since large amounts of nitrogen are mineralized  
100 following potato harvest, straw incorporation possibly  
101 contributes to the prevention of economically and  
102 environmentally relevant post-harvest N losses. In  
103 order to quantify these effects, pre- and post-harvest  
104 soil nitrate was measured in two of the field  
105 experiments.

## 2. Material and methods 106

### 2.1. Field experimental design 107

108 Spreading straw on potato fields shortly after crop  
109 emergence (mulching) was compared to non-mulch-  
110 ing (bare soil) in 11 field experiments. The experi-  
111 ments were conducted on two organically managed  
112 farms in Germany: (A) The experimental farm of the  
113 University of Kassel at Hebenshausen and Neu-  
114 Eichenberg ( $51^{\circ}23'N$ ,  $9^{\circ}55'E$ ) ca. 16 km S of  
115 Göttingen, 220–250 m above sea level with clay–silt  
116 soils on loess (13–15% clay, 78–83% silt, 3–6% sand);  
117 and (B) an arable farm ca. 17 km ESE of Göttingen  
118 ( $51^{\circ}28'N$ ,  $10^{\circ}08'E$ ) ca. 240–280 m above sea level  
119 with loamy soils (20–24% clay, 73–76% silt, 3–6%  
120 sand). Climatic conditions of the experimental years  
121 and locations are summarized in Table 1. For all  
122 experiments mulched and non-mulched plots were  
123 either marked within existing potato fields or were set  
124 up as separate small-scale experiments (Table 2).  
125 Dates for planting, mulching and harvest, as well as  
126 mulch quantities and plot sizes are presented in  
127 Table 2. In all years, weeds were controlled twice  
128 before mulch application with a rotary finger wheel  
129 hoe with ridging discs (site A) or a Wühlmaus Ridging

Table 1  
Air temperature (°C) and precipitation (mm), from April to August in 2001–2003, and the long-term average at two experimental sites

Year	April	May	June	July	August	Whole year
Temperature site A						
2001	7.2	13.7	13.8	18.1	19.4	
2002	8.1	14.3	17.1	19.8	19.9	
2003	7.8	13.6	17.9	18.1	19.8	
1977–2000	7.1	12.0	14.6	16.5	16.4	8.1
Precipitation site A						
2001	60.4	31.8	53.3	62.3	35.8	
2002	48.7	117.4	73.4	33.2	54.5	
2003	25.9	85.4	78.4	s.d. <sup>b</sup>	19.3	
1977–2000	45.2	53.9	75.7	62.7	54.4	635.2
Precipitation site B <sup>a</sup>						
2002	58.9	91.6	78.1	113.5	80.7	
2003	38.7	42.7	64.5	46.3	20.0	
1977–2000	48.3	62.0	78.7	64.7	66.8	708.7

Data from weather station of the University of Kassel agricultural experimental station (site A) and from a Deutscher Wetterdienst (DWD) station (site B).

<sup>a</sup> Temperature data for site B are not available, but temperatures are expected to be similar to those of site A due to the short distance between the two sites and similar altitudes.

<sup>b</sup> s.d.: sampler defect, but own observations indicate that precipitation was below long time average.

Table 2  
Details of experiments: plot size, planting, mulching and harvesting date, mulch quantity, cumulated length of row harvested per plot and precrop

Experiment	Year	Site	Variety	Plot size (m × m)	Experiment type <sup>b</sup>	Planting date	Mulching date	Mulch (t ha <sup>-1</sup> ) (±0.25)	Date of harvest	m harvested per plot	Precrop <sup>f</sup>
1	2001	A	Christa	9 × 9	Extra	23.4	18 + 28.5 <sup>c</sup>	5.0	26 + 27.7 <sup>c</sup>	63	Grass-clover
2	2001	A	Marabel	≥10 × 10 <sup>a</sup>	On-farm	10.5	12.6	3.5	2.9	7	Brussels sprouts
3	2001	A	Rosella	5.25 × 5	On-farm	11.5	21.6	1.25–5 <sup>d</sup>	–	–	Grass-clover
4	2002	A	Christa	9 × 9	Extra	10.4	16 + 26.5 <sup>c</sup>	5.0	14. + 16.8 <sup>c</sup>	63	Grass-clover
5	2002	A	Nicola	9 × 9	Extra	15 + 20.5	3 + 10.6 <sup>c</sup>	4.0	23. + 24.9 <sup>c</sup>	63	Grass-clover
6	2002	B	Christa	9 × 30	On-farm	5.4	17.5	3.5	5.8	27	Carrots
7	2002	B	Nicola	15 × 25	On-farm	8.4	17.5	3.5	28.8	15	Winter wheat
8	2002	B	Nicola	3 × 25	On-farm	8.4	17.5	3.5	28.8	15	Winter wheat
9	2003	A	Marabel	24 × 18	On-farm	17.4	28.5	3.0	3.9	15	Summer wheat
10	2003	A	Rosella	18 × 30	On-farm	17.4	28.5	3.0	4.9	15	Cabbage
11	2003	B	Christa	15 × 27.5	On-farm	26.3	8.5	2.5	2.7	27	Winter Triticale
12	2003	B	Nicola	30 × 27.5	On-farm	15.4	21.5	3.0	26.8	48	Peas

<sup>a</sup> Varied plot size: 10 m × 10 m, 20 m × 20 m and 30 m × 30 m; plot size had no significant effect on yield.

<sup>b</sup> Experiment type; “on-farm” experiments were marked within farmers’ fields, “extra” (small scale) experiments were surrounded by 3-m wide strips of bare soil.

<sup>c</sup> Earlier date in presprouted, later date in non-presprouted potatoes. No significant interaction between mulch and presprouting regarding yield.

<sup>d</sup> Varied amounts: 1.25, 2.5 and 5.0 t/ha.

<sup>e</sup> Harvest of mature tubers occurred blockwise on two dates; haulms had already died back completely before harvest.

<sup>f</sup> Green manure over winter after winter cereals.

Hiller (site B). Haulm death was caused by late blight (*Phytophthora infestans* Mont de Bary) in 2001 and 2002. In 2003, haulms were cut after plant growth had stopped due to hot and dry weather. Chopped straw mulch was applied by hand in experiments 1, 4 and 5; with a Kverneland Round bale chopper (KD 807) in experiments 2, 6 and 7; and with a Hawe Stable Straw Spreader in experiments 8–12. All experiments were conducted in randomized complete block designs with four replicates. Further details of experiments 1, 2, 4 and 5 are presented in Saucke and Döring (2004). In experiments 1, 4, 5 and 12, presprouting of seed tubers was included as an additional factor. As there were no interactions between presprouting and mulching in any case, the presprouting factor is disregarded in this paper.

## 2.2. Soil sampling

Soil was sampled at two depths (0–30 and 30–60 cm) in experiments 1, 4 and 11 with a Göttinger soil sampling set (diameter, 18 mm). Bulk samples of each plot were obtained from 8 (experiment 1) or 10 (experiments 4 and 11) points per plot, with a diagonal sampling line across the plot. Sampling points were chosen half way between the top (ridge) and the bottom (furrow), i.e., on the ridge shoulder. Sampling in experiment 1 was done shortly before harvest (23 July 2001); sampling in experiments 4 and 11 was done at three dates per year (1) at plant emergence (22 April 2002, 22 April 2003), (2) after haulm death shortly before harvest (6 August 2002, 22 July 2003) and (3) 3–6 weeks after harvest and before emergence of the following green manure crop (24 September 2002, 10 September 2003). Samples were cooled in the field and frozen at  $-18^{\circ}\text{C}$  until moisture content was measured (weight loss after 24 h at  $105^{\circ}\text{C}$ ; experiments 1, 4 and 11) and analysis of mineral N was done for samples of experiments 4 and 11 with 100 g soil and  $\text{CaCl}_2$ -extraction (VDLUGA, 1991; König and Fortmann, 1996).

## 2.3. Plant growth parameters

In experiment 1, the chlorophyll content of potato leaves was measured by determination of light transmission at 650 and 960 nm with the Hydro N-Tester of Hydro Agri Ltd., Immingham, UK, which is

based on a SPAD 502 by Minolta Corp. (Kantety et al., 1996; Shaahan and El-Bendary, 1999). Dimensionless output values of the Hydro N-Tester are correlated to chlorophyll content of tobacco leaves ( $r^2 = 0.95$ ) and to N content in potato leaves ( $r^2 = 0.88$ ) (Neukirchen and Lammel, 2002). On 25 June 2001, before flowering and at about 90% crop cover, 30 plants per plot were sampled, with one leaf from the upper and one from the middle part of each plant.

Plant height was measured in cm in experiments 7, 9, 11 and 12 as the distance from the top of the ridge to the highest part of the randomly chosen plant. The number of plants sampled per plot and the sampling dates are summarized in Table 5.

## 2.4. Weed assessments

Weed development was investigated in five experiments. In experiments 1, 9 and 12, a sampling frame of  $0.40\text{ m} \times 1.60\text{ m}$  was randomly thrown into the plot and adjusted so that the longer side was parallel with the rows; two positions were sampled per throw (a) the bottom half of the ridge profile (“in furrows”) and (b) the adjacent top half (“on ridges”). Weeds were counted and weed cover was estimated. The number of subsamples (throws) per plot is given in Table 6.

In experiments 7 and 8, the above ground biomass of weeds was cut from four randomly chosen sampling areas per plot, measuring  $1.50\text{ m} \times 1.50\text{ m}$  each. The weeds were dried at  $80^{\circ}\text{C}$  until constant weight.

## 2.5. Harvest and yield measurement

Harvesting was done with a “Samro Spezial” potato lifter with cleaning drum in experiments 1, 4 and 5 and by hand in all other experiments. Per plot, seven subsamples were taken in experiments 1, 4, and 5; two in experiment 2; nine in experiments 6 and 11; five in experiments 7–10; and sixteen in experiment 12; row length per subsample was 9 m in experiments 1, 4, and 5; 3.5 m in experiment 2; and 3 m in all other experiments. The cumulative row length harvested per plot is given in Table 2. Harvested tubers were sorted with a Schmotzer shaking-grid-type potato sorter, partitioning the lots into three fractions (<35, 35–65 and >65 mm in experiments 1 and 2; and <35, 35–55 and >55 mm in all other experiments).

218 2.6. *Soil erosion*

219 Soil erosion was measured in an unreplicated  
 220 artificial rain experiment (experiment 3; at 20% crop  
 221 cover and with a slope of 8%), using a mobile rainfall  
 222 simulator developed by Kainz and Eicher (1990)  
 223 (Auerswald and Eicher, 1992; Auerswald et al., 1992;  
 224 Kainz et al., 1992), with four horizontally oscillating  
 225 Veejet 80100 nozzles (Moore et al., 1983). The  
 226 maximum rain drop size is 10–20 mm diameter and  
 227 13% of drops are below 3 mm (Hassel and Richter,  
 228 1992). Nozzle height (2.8 m) and water pressure  
 229 (42.2 kPa) resulted in an adjusted dropping height of  
 230 3.5 m. The rain interval was 60 min per plot, the first  
 231 20 min with artificial rain intensity of 60 mm h<sup>-1</sup>, the  
 232 last 40 min with 80 mm h<sup>-1</sup>. The sum of applied rain  
 233 within 1 h of simulation was 73 mm. The kinetic energy  
 234 of the first 20 min was 382 J m<sup>-2</sup>, of the last 40 min  
 235 1012 J m<sup>-2</sup> (Hassel and Richter, 1992). Treatments  
 236 were mulch of chopped winter wheat straw (mean  
 237 length 58 mm; S.D. 41 mm) at 1.25, 2.5 and 5.0 t ha<sup>-1</sup>  
 238 and uncut (long) straw at 2.5 t ha<sup>-1</sup>, as well as an  
 239 unmulched control. Runoff delay after starting the  
 240 artificial rainfall was determined and runoff was  
 241 continuously measured and collected. Sediment con-  
 242 centration (g l<sup>-1</sup>) was determined by drying runoff at  
 243 105 °C (Brandt, 1997). Afterflow was measured as the  
 244 time between end of artificial rainfall and end of runoff.

245 2.7. *Estimation of area covered by varied amounts of*  
246 *straw*

247 In order to establish the relationship between the  
 248 quantity of straw applied and the percentage of the  
 249 area covered by straw mulch, wheat straw (dry matter  
 250 content 94.0 ± 0.1%) was distributed on the object  
 251 table (48.5 cm × 31.5 cm) of a leaf area meter (Delta-  
 252 T Devices Ltd., Cambridge, UK; Monitor Hitachi  
 253 VM900, Interface RS 232c; Video-Camera TC 1005/  
 254 01X, RCA, Lancaster). The amount of straw on the  
 255 object table was gradually increased in 5 g steps from  
 256 0 to 50 g. Three treatments were measured with three  
 257 replicates each: (i) straw cut into regular, 50 mm long  
 258 pieces (ca. 5 mm wide; double-sided internodes only);  
 259 (ii) chopped straw, piece length <35 mm (measured  
 260 from *n* = 344 pieces ≥10 mm); and (iii) unchopped  
 261 straw, average piece length 75 mm (measured from  
 262 50 g, *n* = 833 pieces; S.D. = 58 mm; 25% of pieces

>100 mm). To achieve a random distribution of the  
 straw on the object table, the straw was cumulatively  
 thrown from a height of 2.32 m through a cardboard  
 tunnel (ground area: 34 cm × 26 cm) placed vertically  
 on the object table; the tunnel was carefully removed  
 from the object table before each area measurement.

269 2.8. *Statistical analysis*

270 Statistical analyses were performed with SAS  
 271 v6.12 (SAS Institute Inc., 1989, 1990). Percentage  
 272 values, such as tuber size fractions, weed cover  
 273 estimates and soil moisture contents, were arcsin-  
 274 square-root transformed before ANOVA. Untrans-  
 275 formed data are presented.

276 3. *Results and discussion*277 3.1. *Soil moisture*

278 Soil moisture measured directly before harvest in  
 279 three experiments. was not affected significantly by  
 280 mulching (Table 3).

281 While it is well established that straw mulch  
 282 increases soil moisture by reduction of evaporation  
 283 (Esselen, 1937; Russel, 1940; Turk and Partridge,  
 284 1947) and increase of infiltration (Duley and Kelly,  
 285 1939) it may also reduce soil moisture by intercepting  
 286 precipitation and preventing rain from penetrating the  
 287 soil, in cases of frequent but small rainfall (Griffith,  
 288 1952, cited in Jacks et al., 1955, p.16). In this study,  
 289 however, looking at the large amount of precipitation  
 290 in the two weeks before the soil moisture sampling  
 291 date (48.2, 27.8 and 92.3 mm in experiments 1, 4, and  
 292 11, respectively), interception is unlikely to be the  
 293 reason for soil moisture being unaffected by mulching.  
 294 Possibly, the heavy rainfall shortly before sampling  
 295 may also have nullified any moisture conserving  
 296 effects of straw mulch.

297 It is known that the moisture conserving effect of  
 298 straw mulch increases with the amount applied  
 299 (Russel, 1940). Verma and Kohnke (1951, p. 150)  
 300 stated that an amount of 3000 pounds of mulch per  
 301 acre [=3.4 t ha<sup>-1</sup>] is about the smallest rate that is  
 302 effective in evaporation control. Therefore, the  
 303 relatively small amounts of straw applied would not  
 304 be expected to be effective in conserving soil moisture.

Table 3

Effect of straw mulch in potatoes on soil moisture shortly before harvest (wt%): means  $\pm$  S.E.

Soil moisture pre-harvest	Experiment 1 (2001, $n = 8$ )		Experiment 4 (2002, $n = 4$ )		Experiment 11 (2003, $n = 4$ )	
	0–30 cm	30–60 cm	0–30 cm	30–60 cm	0–30 cm	30–60 cm
Unmulched	17.7 $\pm$ 0.5	19.0 $\pm$ 1.1	21.1 $\pm$ 2.8	20.2 $\pm$ 2.3	8.8 $\pm$ 0.3	11.7 $\pm$ 0.2
Mulched	18.9 $\pm$ 0.8	18.0 $\pm$ 0.6	21.1 $\pm$ 2.3	20.6 $\pm$ 3.1	9.3 $\pm$ 0.3	11.8 $\pm$ 0.2
L.S.D. 5% (untransformed)	1.6 ns	2.0 ns	2.6 ns	1.7 ns	1.6 ns	1.1 ns

ns: difference not significant (both for untransformed and angle-transformed data).

## 305 3.2. Soil nitrate dynamics

306 At emergence and immediately before harvest,  
 307 only small and non-significant differences in soil  
 308 nitrate between mulched and unmulched plots were  
 309 found (Table 4). Nitrogen mineralization after the  
 310 harvest process lead to a post-harvest increase of  
 311 nitrate in the soil (62 and 51 kg NO<sub>3</sub>-N ha<sup>-1</sup> in the  
 312 unmulched soil, experiments 4 and 11, respectively).  
 313 The post-harvest amount of nitrate was greater in the  
 314 unmulched than in the mulched plots with a total  
 315 difference of 33.8 kg NO<sub>3</sub>-N ha<sup>-1</sup> in experiment 4  
 316 (not significant) and 17.6 kg NO<sub>3</sub>-N ha<sup>-1</sup> in experi-  
 317 ment 11 (significant at  $p = 0.035$ ; Table 4).

318 The reason for this is seen in an immobilization of  
 319 nitrogen after incorporation of the (partially decayed)  
 320 straw into the soil due to the high C/N-ratio of straw

(Cheshire et al., 1999). The C/N-ratio of the straw in  
 experiment 4 was determined as 76.7; this value is  
 well below the long-time average C/N-ratio of 100 for  
 winter wheat straw presented by Boguslawski and  
 Debruck (1977). Per tonne straw applied, ca. 6.8 and  
 7.0 kg N (experiments 4 and 11, respectively) were  
 immobilized; this immobilization rate is at the upper  
 end of the range (1–7 kg N t<sup>-1</sup>) summarized by  
 Christensen and Olesen (1998).

330 3.3. Parameters of plant nutritional status and plant  
331 growth

332 Hydro N-Tester values, as a measure of the  
 333 nutritional status of the plant, were significantly  
 334 reduced by straw mulch application in experiment 1  
 335 (Fig. 1). Plant height was slightly but significantly

Table 4

Effect of straw mulch applied to potatoes (var. Christa) on soil nitrate-N (kg ha<sup>-1</sup>) in two experiments<sup>a</sup>: means  $\pm$  S.E.,  $n = 4$ 

Soil nitrate <sup>a</sup>	Experiment 4 (2002)			Experiment 11 (2003)		
	0–30 cm	30–60 cm	Sum (0–60 cm)	0–30 cm	30–60 cm	Sum (0–60 cm)
At emergence (before mulching) <sup>b</sup>						
Unmulched	70.2 $\pm$ 12.5	40.4 $\pm$ 11.4	110.6 $\pm$ 23.6	40.1 $\pm$ 4.1	14.3 $\pm$ 2.7	54.4 $\pm$ 6.7
Mulched	74.3 $\pm$ 7.3	39.4 $\pm$ 10.2	113.7 $\pm$ 17.4	36.2 $\pm$ 3.9	14.0 $\pm$ 3.5	50.2 $\pm$ 7.3
Pre-harvest (after haulm death) <sup>b</sup>						
Unmulched	25.3 $\pm$ 4.8	22.7 $\pm$ 5.2	48.0 $\pm$ 9.7	20.7 $\pm$ 1.1	3.2 $\pm$ 0.2	23.9 $\pm$ 1.0
Mulched	24.4 $\pm$ 2.6	21.8 $\pm$ 5.8	46.2 $\pm$ 8.3	20.6 $\pm$ 2.1	4.5 $\pm$ 1.1	25.1 $\pm$ 1.6
Post-harvest						
Unmulched	69.4 $\pm$ 16.2	40.6 $\pm$ 11.7	110.0 $\pm$ 27.8	61.1 $\pm$ 8.1	13.8 $\pm$ 4.7	74.9 $\pm$ 11.1
Mulched	46.4 $\pm$ 10.2	29.8 $\pm$ 7.2	76.2 $\pm$ 17.2	48.7 $\pm$ 6.7	8.7 $\pm$ 1.3	57.3 $\pm$ 8.0
Post-harvest difference						
Unmulched-Mulched	23.0 $\pm$ 11.7	10.8 $\pm$ 7.2	33.8 $\pm$ 18.8	12.5 $\pm$ 2.6	5.1 $\pm$ 4.1	17.6 $\pm$ 4.8
LSD (5%)	37.1 ns	23.0 ns	59.8 ns	8.3*	13.2 ns	15.2*

ns: not significant.

<sup>a</sup> For details of experimental conditions see Table 2; for sampling dates see text (Section 2.2).<sup>b</sup> There were no significant differences between mulched and unmulched treatments concerning soil nitrate at emergence and pre-harvest.\*  $p < 0.05$ .

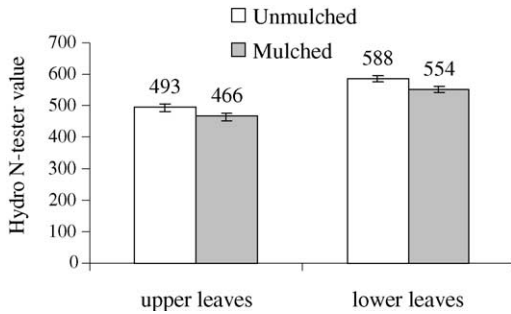


Fig. 1. Hydro N-Tester value as affected by straw mulching (experiment 1). Means ± S.E.; n = 8. Mulching effect significant at p < 0.001; effect of leaf position significant at p < 0.001. Interaction between mulching and leaf position is not significant.

Table 5  
Effect of straw mulching in potatoes on plant height in cm

Experiment	7	9	11	12	12
Variety	Nicola	Marabel	Christa	Nicola	Nicola
Sampling date	19.06.02	09.07.03	12.06.03	12.06.03	09.07.03
Plants/plot	16	16	8	8	8
Replications	8	4	4	8	16
Unmulched	38.1	55.5	41.2	47.8	64.9
Mulched	36.0	53.3	42.0	48.5	63.3
L.S.D. 5%	1.5*	3.8 ns	2.6 ns	2.8 ns	1.57*

ns: not significant.

\* p < 0.05.

3.4. Weeds

The most dominant weed species were *Fumaria officinalis* in experiment 1, *Polygonum persicaria* and *Cirsium arvense* in experiments 7 and 8, *Thlaspi arvense* and *Chenopodium album* in experiment 9 and *Stellaria media* and *Chenopodium album* in experiment 12. There were no consistent effects of mulching on the number of weeds, weed cover and biomass (Table 6; Fig. 2). However, the sampling position with respect to the ridges and the timing within the season appeared to interact with the effect of mulching in experiment 1. Earlier in the season (6 June) mulching increased the number and cover of weeds, while three

reduced by straw mulch in two out of five cases, i.e., in experiments 7 and 12 on the later sampling date, but it was not influenced in experiments 9 and 11, and in experiment 12 on the earlier sampling date (Table 4).

One reason for decreased growth might be possibly lower soil nitrate levels under straw mulch during the vegetation period (Albrecht, 1922; Albrecht and Uhland, 1925), but—again probably due to the small amount of straw applied—growth parameters were not consistently affected (Table 5).

Table 6  
Effect of straw mulch and sampling position on weed counts (number of plants per m<sup>2</sup>) and weed cover (%) in experiment 1, 9 and 12

Parameter	Count/m <sup>2</sup>				Cover (%)				
	Experiment (date)								
	1 (06.06)	1 (27.06)	9 (12.06)	12 (18.06)	1 (06.06)	1 (27.06)	9 (12.06)	12 (18.06)	12 (09.07)
Unmulched in furrows	10.4	82.0	103.3	31.4	0.0	2.1	1.3	1.7	10.5
Mulched in furrows	15.6	24.4	56.8	30.4	1.8	3.2	1.0	1.9	10.3
Unmulched on ridges	5.2	20.1	21.5	3.9	0.5	1.2	0.7	0.3	— <sup>a</sup>
Mulched on ridges	16.9	10.1	19.7	3.3	3.0	2.2	0.3	0.4	—
Significance level for									
Mulching effect	*	**	ns	ns	**	ns	*	ns	ns
Position effect	ns	**	***	***	ns	ns	**	***	—
Interaction	ns	ns	ns	ns	ns	ns	ns	ns	—
Error d.f.	21	21	9	9	21	21	9	9	7
Number of subsamples	2	2	2	8	2	2	2	8	10

ns: not significant.

<sup>a</sup> Not sampled.

\* 0.01 < p < 0.05.

\*\* 0.001 < p < 0.01.

\*\*\* p < 0.001.

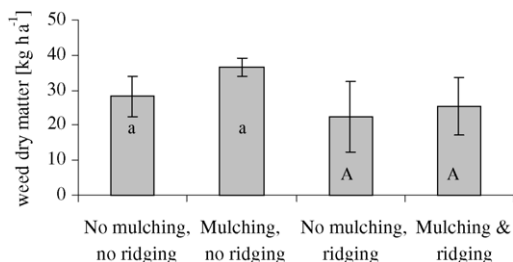


Fig. 2. Weed dry matter ( $\text{kg ha}^{-1}$ ) on 9 July 2002, as affected by mulching in experiment 7 (ridged after mulching, upper case letters) and experiment 8 (not ridged after mulching, lower case letters). Means  $\pm$  S.E.;  $n = 4$ . Means with the same letter within the same case (i.e., within the same experiment) are not statistically different. Statistical comparisons regarding ridging are not possible, as this factor was not randomized over the two (adjacent) experiments.

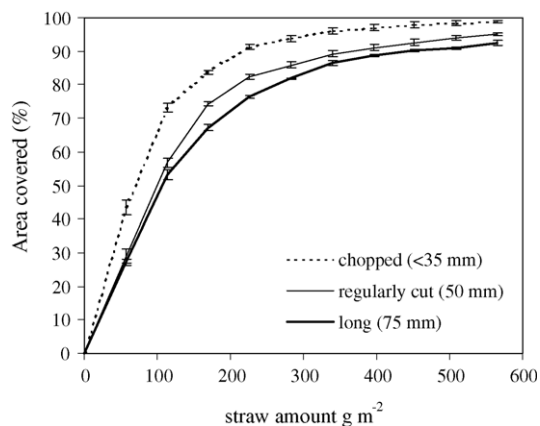


Fig. 3. Area covered by varied amounts of wheat straw of different size classes, measured by leaf area meter; means  $\pm$  S.E.,  $n = 3$ .

360 weeks later (27 June) the number of weeds was  
 361 reduced; this reduction was significant overall (i.e., for  
 362 both sampling positions together) and for the lower  
 363 sampling position (“in furrows”), but not for the top  
 364 half of the ridge profile (Fig. 3).

365 While weed reduction by light-excluding mulches  
 366 has widely been reported (Rowe-Dutton, 1957; Prihar  
 367 et al., 1976), a possible compensatory effect occurs  
 368 when weeds benefit from increased soil moisture  
 369 under light mulches (Jacks et al., 1955; Jalota and

Prihar, 1979), and this may explain the increased  
 370 number of weeds early in the season in experiment 1.  
 371 After several weeks, the straw mulch had partly slid  
 372 off the top half of the ridge and accumulated on the  
 373 bottom where it impeded weed growth. Indirect  
 374 detrimental effects of mulch on yield through the  
 375 promotion of weeds have been reported (Zhivan, 1935,  
 376 cited in Jacks et al., 1955), but here, for a negative  
 377 effect of weeds on yield, overall weed cover was too  
 378

Table 7  
 Effect of straw mulching on tuber yield of potatoes

Experiment	Year	Site	Variety	d.f.	Total yield (dt/ha) <sup>c</sup>		Effect of mulching (%)	Fractions: absolute difference (mulched–unmulched) (%)	
					Unmulched	Mulched		Small fraction <sup>d</sup>	Large fraction <sup>d</sup>
1	2001	A	Christa	6	359 $\pm$ 8	375 $\pm$ 7	4.3 ns	-0.6 $\pm$ 0.2*	1.5 $\pm$ 1.1 ns
2	2001	A	Marabel	4	432 $\pm$ 9	458 $\pm$ 8	6.1 ns	0.1 $\pm$ 0.9 ns	-3.5 $\pm$ 2.3 ns
4	2002	A	Christa	7	142 $\pm$ 18	138 $\pm$ 18	-3.0 ns	-2.9 $\pm$ 2.8 ns	1.5 $\pm$ 1.1 ns
5	2002	A	Nicola	7	150 $\pm$ 19	159 $\pm$ 19	6.0 ns	-0.2 $\pm$ 1.3 ns	2.5 $\pm$ 2.1 ns
6	2002	B	Christa	2	146 $\pm$ 12	153 $\pm$ 3	4.8 ns	-0.8 $\pm$ 0.6 ns	1.4 $\pm$ 1.2 ns
7 <sup>a</sup>	2002	B	Nicola	7	193 $\pm$ 12	187 $\pm$ 14	-3.2 ns	2.9 $\pm$ 2.2 ns	-1.5 $\pm$ 1.5 ns
8	2002	B	Nicola	3	231 $\pm$ 8	204 $\pm$ 21	-11.5 ns	2.7 $\pm$ 1.6 ns	-3.3 $\pm$ 2.6 ns
9	2003	A	Marabel	3	306 $\pm$ 25	299 $\pm$ 13	-2.3 ns	0.3 $\pm$ 0.5 ns	-5.9 $\pm$ 1.1*
10 <sup>b</sup>	2003	A	Rosella	3	415 $\pm$ 13	388 $\pm$ 13	-6.5 ns	0.05 $\pm$ 0.1 ns	-1.9 $\pm$ 3.6 ns
11	2003	B	Christa	3	292 $\pm$ 11	307 $\pm$ 23	5.2 ns	0.1 $\pm$ 0.4 ns	1.6 $\pm$ 0.3*
12	2003	B	Nicola	3	378 $\pm$ 17	371 $\pm$ 12	-1.8 ns	0.2 $\pm$ 0.1 ns	0.9 $\pm$ 1.1 ns

ns: difference not significant; means  $\pm$  S.E.

<sup>a</sup> Experiment 7: Straw was partly incorporated into soil with finger wheel hoe 6 weeks after mulching.

<sup>b</sup> Experiment 10: Straw was partly incorporated into soil due to strong rainfall (ca. 50 mm in 2 h) already 3 days after mulching.

<sup>c</sup> Total yield of Experiments 1–5: Figures have already been presented in Saucke and Döring (2004).

<sup>d</sup> Small fraction < 35 mm; large fraction > 65 mm in experiments 1 and 2 and >55 mm in experiments 4–11.

\*  $p < 0.05$ .

379 little. The main reason why weed growth was not  
380 influenced consistently by straw mulch in the  
381 experiments presented is again seen in the compara-  
382 tively small application rates. Bushnell and Welton  
383 (1931) found that at application levels below 8 t/acre  
384 [=19.75 t ha<sup>-1</sup>], annual weeds readily penetrated the  
385 mulch. Similarly, Hembry and Davies (1994) found  
386 weed growth still occurring at 20 t ha<sup>-1</sup> of straw  
387 mulch, although with few weeds.

### 388 3.5. Yield and tuber size fractions

389 Response of yield to straw mulch was not  
390 significant in any experiment (Table 7) and the trends  
391 of mulching effects on yield were evenly distributed  
392 (positive trend in five experiments., negative trend in  
393 six experiments.). Equally, tuber size fractions were  
394 not significantly affected by mulching, except for  
395 three experiments (experiments 1, 9 and 11), but again  
396 with no consistent direction.

397 These results are in agreement with recent  
398 investigations on straw mulch effects from temperate  
399 climates, which also did not show any significant yield  
400 response of potatoes to straw mulch (Stoner et al.,  
401 1996; Edwards et al., 2000, data not presented). As  
402 pointed out by Jacks et al. (1955), mulching affects  
403 crop yields in many and complex ways. Higher yields  
404 under mulch have mostly been attributed to increased  
405 soil moisture under arid and semiarid conditions  
406 (Singh et al., 1987, 1988; Saha et al., 1997; Tiwari  
407 et al., 1998; Tolk et al., 1999; Ramalan and  
408 Nwokeocha, 2000; Chandra et al., 2002) but even  
409 in the comparatively hot dry summer of 2003 (see  
410 Table 1) yields were not significantly affected by straw  
411 mulching. Reasons for the tuber yield not being  
412 affected by straw mulch may include the compensa-

413 tion ability of the plant under water stress conditions,  
414 the high water holding capacity of the soils and the  
415 comparatively low evaporativity during the experi-  
416 mental periods; however, the main reason is seen in the  
417 low amount of straw applied, as already soil moisture  
418 was not influenced significantly by mulching (see  
419 above).

### 3.6. Soil erosion

420 Soil loss was greatest in the unmulched plot with  
421 1606 g m<sup>-2</sup> (Table 8); similar values were found by  
422 Lal (1975) with 1219 and 2706 g m<sup>-2</sup> on 5 and 10%  
423 sloping unmulched soil, respectively. Even very small  
424 amounts of straw mulch (1.25 t ha<sup>-1</sup>) decreased soil  
425 loss and sediment concentration in runoff. While cut  
426 straw reduced soil loss by 97.4–98.4% compared with  
427 untreated soil, reduction of soil loss by long straw  
428 (2.5 t ha<sup>-1</sup>) was less effective (reduction by 91.7%).  
429 Similar results were found in other investigations.  
430 With straw application levels of 2 and 4 t ha<sup>-1</sup> at 10%  
431 slope, Lal (1975) found soil loss reduced by 97 and  
432 99.6%, respectively, compared to soil loss in  
433 unmulched treatments. On a 12.5% sloping silt loam,  
434 an application of ca. 5 t ha<sup>-1</sup> lead to soil loss reduction  
435 by 98.0–99.9% (Borst and Woodburn, 1942b).

437 During rain simulation the straw was partly washed  
438 from ridges into furrows and formed micro-dams,  
439 building a lined-up microrelief which retained the  
440 surface rainwater in small hollows as was already  
441 observed by others (Roth and Helmig, 1992; Brandt,  
442 1997; Roth, 1998). As a result, afterflow was  
443 increasingly delayed with increasing straw quantity  
444 from 2.7 min in untreated to 39.7 min in 5 t ha<sup>-1</sup> straw  
445 mulch. Long straw also formed dams and built up  
446 hollows, but the effect of runoff filtration was less

Table 8

Effect of straw mulch quantity and straw texture on runoff, after flow, sediment concentration and soil loss—results of rain simulations

	Mulch quantity (t ha <sup>-1</sup> ) (mulch texture)				
	0	1.25 (cut)	2.5 (cut)	5.0 (cut)	2.5 (long)
Start runoff (min)	21.7	21.4	32.2	23.0	22.7
Afterflow (min)	2.7	13.4	38.3	39.7	33.4
Mean sediment concentration (g l <sup>-1</sup> )	69.0	3.4	2.2	1.1	10.5
Max sediment concentration (g l <sup>-1</sup> )	101.7	5.1	8.0	1.9	41.4
Soil loss per plot (g)	10357	199	270	170	857
Soil loss (g m <sup>-2</sup> )	1606	31	42	26	133
Soil loss (%)	100	1.9	2.6	1.6	8.3

447 marked than in the treatments with chopped straw.  
 448 Due to the application of straw mulch onto ridges and  
 449 their transportation into furrows by the rain, the effect  
 450 of reduced soil crusting on the upper half of the ridge  
 451 was small. Soil crusting, as a result of the artificial  
 452 rain, lead to considerable runoff. The main effect of  
 453 straw mulch is seen in the sediment retention (Brandt  
 454 and Wildhagen, 1998). Therefore, only small amounts  
 455 of straw are necessary for avoiding soil erosion in  
 456 ridge till systems like potato cultivation.

### 457 3.7. Coverage by straw mulch as affected by the 458 amount applied

459 The relationship between the area covered by straw  
 460 mulch layer and the quantity of straw applied follows a  
 461 typical saturation function for all three straw piece  
 462 lengths (Fig. 1). This is in accordance with the findings  
 463 of Nill and Nill (1993). Regarding the length of straw  
 464 pieces, chopped straw is more economic in covering  
 465 the soil surface than long straw, covering the same area  
 466 (e.g., 90%) with much less weight ( $216 \text{ g m}^{-2}$   
 467  $= 2.16 \text{ t ha}^{-1}$ ) than long straw ( $443 \text{ g m}^{-2}$ ). The main  
 468 reason for this is seen in the fact that the uncut material  
 469 is double-sided and therefore can only cover half of  
 470 the area per unit weight than single-sided straws that  
 471 have been split by chopping. In addition, the smaller  
 472 pieces of chopped straw may fit more properly into  
 473 gaps and form a smooth, flat mat more readily than the  
 474 long pieces of uncut straw.

475 Applying the figures from the leaf area meter to a  
 476 (ridged) soil may only be done carefully. First, the soil  
 477 surface usually is considerably rougher in contrast to  
 478 the smooth object table used; this will probably  
 479 increase the amount of straw needed to cover a given  
 480 soil area. Second, in the field the straw (with a typical  
 481 range of 80–90% dry matter) is not as dry as the  
 482 material used here. Despite these restrictions, the data  
 483 are in very good accordance with those presented by  
 484 Borst and Woodburn (1942b), who estimated that 1 t/  
 485 acre of long straw ( $=2.47 \text{ t ha}^{-1}$ ) covered 75–85% of  
 486 an unridged soil, although figures for straw dry weight  
 487 were not given.

488 Finally, it should be considered that by ridging, the  
 489 area to be covered approximately increases by a factor  
 490 of  $f = (x^2 + y^2)^{0.5}/y$ , where  $x$  = height of ridge from  
 491 bottom to top and  $y$  = distance between rows. At  $x$  =  
 492 30 cm ridge height and  $y$  = 75 cm row spacing, this

493 factor is  $f = 1.077$ , e.g.,  $3.0 \text{ t ha}^{-1}$  for flat surfaces  
 494 would have to be adjusted to  $3.23 \text{ t ha}^{-1}$  on ridged  
 495 surfaces. The results presented here indicate that  
 496  $5 \text{ t ha}^{-1}$  of chopped straw covers >95% of the ridged  
 497 soil.

## 498 4. Conclusion

499 Under the edaphic and climatic conditions of the  
 500 present study (loamy silt soils, temperate climate) and  
 501 with light to moderate quantities of straw, yield was  
 502 not affected by straw mulching. This offers the  
 503 possibility of benefitting from virus vector and soil  
 504 erosion control functions of straw mulch, without the  
 505 risk of yields being reduced when summers are wet  
 506 and cool. At the same time, at lower application levels  
 507 costs for material and spreading are reduced. More-  
 508 over, preventing soluble N from being leached after  
 509 harvest by mulch application was shown to be possible  
 510 even at small straw application rates and can be seen as  
 511 a further economic benefit.

512 Soil moisture was not significantly affected by  
 513 mulching at small or moderate application levels. This  
 514 is considered as a further important prerequisite for the  
 515 practicability of straw mulch application, as mechan-  
 516 ical tuber harvesting will not be delayed or impeded by  
 517 above-optimum soil moisture, especially with heavier  
 518 soils.

519 Finally, in this study, moderate amounts of straw  
 520 neither reduced nor enhanced weeds significantly. A  
 521 prerequisite for compatibility of straw mulch  
 522 application and mechanical weed control was,  
 523 however, that a sufficient weed control was possible  
 524 before straw application. This kept overall weed  
 525 levels moderate during the whole vegetation period  
 526 in all experiments. If weeding is done after mulching,  
 527 i.e., when the straw is incorporated during the  
 528 growing period, there will be the risk of N  
 529 immobilization and the straw cover will at least  
 530 partly be destroyed and optically mediated effects on  
 531 virus vectors will be lost. On the other hand, the  
 532 benefits of moving and aerating the soil by  
 533 mechanical weeding, principally N mineralization,  
 534 could economically overcompensate these effects.  
 535 Due to the possibly conflicting objectives of good  
 536 straw mulch coverage on the one hand, and the need  
 537 for mechanical weed control measures in organic

538 potato growing on the other hand, weed control in  
539 organic straw mulch systems requires further  
540 attention.

541 For the re-adoption of the straw mulch application,  
542 chopped instead of long straw should be used, as it is  
543 most effective in covering the soil; this is particularly  
544 important when a complete coverage of the soil is  
545 regarded as a goal, e.g., in the virus vector control,  
546 where the effect of mulch is based on optical  
547 mechanisms (Döring et al., 2004).

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