Straw mulch in organically grown potatoes

Evaluation and optimisation for virus vector control

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by

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Summary

1. In order to evaluate effects of straw mulch applied at 2.5 – 5 t ha^{-1} in organically grown potatoes (*Solanum tuberosum* L.), 21 field experiments were conducted over five years at two locations (Northern Hessen and Southern Niedersachsen, Germany). The experimental sites were characterised by temperate climate conditions (635 – 709 mm precipitation year^{-1}; 8.1°C mean air temperature) and loamy silt soils. The main focus of the study was on aphids and the aphid-transmitted *Potato virus Y* (PVY). This disease is a main problem in seed potato production. In addition to virus and vectors, associated agronomic effects of straw mulch were studied.
2. Straw mulch significantly reduced the incidence of PVY. It was most effective as a protectant for young plants against PVY, thus when a high vector pressure occurred early in the year. Combined mulching and presprouting (chitting) had a synergistic effect on the reduction of PVY incidence, with mulching affecting early vectors while the chitted plants exhibited adult plant resistance earlier, thus protecting from late occurring vectors.
3. Straw mulch reduced aphid infestation on potato leaves and populations of potato-colonising aphids, but did not affect population growth rates. Scaling up the area mulched stepwise from 100 m^2 to 900m^2 consistently kept aphid infestation at reduced levels.
4. In a small scale experiment, straw mulch resulted in a reduction of the number of winged aphids landing in green water traps, compared to traps placed on bare soil; this effect was significant with amounts of 200 g straw m^{-2} and $\geq$ 400 g m^{-2}, but increasing the straw quantity beyond 200 g m^{-2} did not cause a further significant aphid reduction.
5. In two further field experiments in 2003, aphid landing in green water traps placed on various backgrounds was tested, including differently coloured plastic sheets, straw and uncovered soil as backgrounds. Aphid catches were highest in traps on uncovered background (soil), and lowest in traps on white or silver backgrounds. For seven aphid species there was a negative correlation between UV-reflectance (320 – 400 nm) of backgrounds and log(N+1)-transformed number of individuals. However, the effect of straw mulch (reduced aphid catches with straw compared to soil), could not be attributed to differences in UV-reflectance, as the UV reflectance was almost identical in soil and straw.
6. Tuber yield and tuber size distribution were not influenced significantly or in a uniform direction by straw mulch application in eleven field experiments, conducted over four years.
7. There was no consistent effect of straw mulch on weed parameters as number of weeds, weed cover and above-ground biomass of weeds.
8. The fact that yield and weed development were not significantly affected by straw mulch is largely attributed to the relatively low amounts of straw applied, which were chosen for the primary purpose of vector control.

9. The risk of undesirable post harvest N-leaching was reduced by straw mulch due to the immobilisation of nitrate-N after harvest at 6.8 – 7.0 kg N t^{-1} straw in two experiments (18 – 34 kg NO_3–N ha^{-1}).
10. Soil erosion was greatly reduced (by >97 %) in a rain simulation experiment on a 8 % sloping potato field with 20 % crop cover.
11. Severity of late blight (*Phytophthora infestans*) was estimated in five of the experiments at 3 – 7 dates per experiment. Straw mulch had no significant effect on late blight severity, measured as relative area under the disease progress curve, in any of the experiments, but a trend reducing late blight by straw mulch was observed in all five experiments.
12. Infestation with sclerotia of black scurf (*Rhizoctonia solani*) on harvested tubers, assessed on 100 – 220 tubers per plot, was not influenced consistently by straw mulch, with effects being non-significant in eight out of nine experiments.
13. Effects of straw mulch on microclimate, measured in one field experiment, were dependent on the time of the day, with the air in mulched plots being moister and cooler at night and dryer and warmer during the day. This effect was less marked in the period 4 – 6 weeks after mulching than in the fortnight directly after mulching.
14. Prospects and constraints of straw mulch application in organic potato production are discussed and parameters for optimisation are suggested.

Zusammenfassung

1. Um die Wirkung von Strohmulch (2.5 – 5 t ha^{-1}) in ökologisch angebauten Kartoffeln (*Solanum tuberosum* L.) zu untersuchen, wurden 21 Feldversuche über fünf Jahre an zwei Standorten in Nord-Hessen und Süd-Niedersachsen durchgeführt. Die Versuchsflächen waren durch ein gemäßigtes Makroklima (635 – 709 mm Niederschlag pro Jahr; 8.1°C mittlere Lufttemperatur) und schluffig-lehmige Böden gekennzeichnet. Das Hauptaugenmerk der Untersuchung lag auf Blattläusen und dem von ihnen übertragenen Kartoffel-Virus Y (PVY). Diese Krankheit stellt ein Hauptproblem in der Pflanzkartoffelerzeugung dar. Zusätzlich wurden Effekte von Strohmulch in Kartoffeln auf agronomische Parameter (Ertrag u.a.) untersucht.
2. Strohmulch führte zu einer signifikanten Reduktion der mit PVY infizierten Ernteknollen. Die Reduktion war am stärksten, wenn der Vektordruck im Frühjahr am höchsten war. Die kombinierte Anwendung von Strohmulch und Vorkeimen hatte einen synergistischen Effekt bei der Virusreduktion: während Strohmulch bei starkem Frühjahrsflug der Vektoren wirksam war, konnte Vorkeimen in Jahren mit schwachem Frühjahrsflug aber stärkerem Sommerflug durch frühere Ausbildung der Altersresistenz Virusinfektionen vermindern.
3. Strohmulch verminderte den Blattlausbefall auf Kartoffelblättern und die Populationen kartoffelbesiedelnder Läuse, jedoch nicht die Wachstumsraten der Blattlauspopulation. Bei der schrittweisen Vergrößerung der Versuchsflächen von 100 m² auf 900m² blieb der Blattlausbefall in den gemulchten Flächen gegenüber der ungemulchten Kontrolle auf reduziertem Niveau.
4. In einem Kleinparzellenversuch führte Strohmulch zu einer Verminderung der Anzahl gefügelter Blattläuse in Grünschalen, im Vergleich zu Grünschalen auf brachem Boden. Dieser Effekt war signifikant mit 200 g Stroh pro m^2 und Mengen über 400 g m^{-2}. Jedoch führte eine Steigerung der Menge über 200 g m^{-2} hinaus nicht zu einer zusätzlichen signifikanten Verminderung der Blattlauszahlen.
5. In zwei weiteren Feldexperimenten im Jahr 2003 wurde die Zahl geflügelter Blattläuse in Grünschalen erfaßt, die auf verschiedene Hintergründe gestellt wurden. Dabei wurden verschiedenfarbige Plastikfolien, Stroh und unbedeckter Boden als Hintergründe verwendet. Die Blattlausfänge waren am höchsten in den Fallen auf unbedecktem Boden, während sie am geringsten in Fallen auf weißem oder silbernem Hintergrund waren. Bei sieben Blattlausarten korrelierte die UV-Reflexion (320 – 400 nm) der Hintergründe negativ mit der log(N+1)-transformierten Individuenzahl der Läuse. Strohmulch reduzierte auch hier im Vergleich zu unbedecktem Boden die Blattlauszahlen, jedoch war dieser Effekt nicht auf Unterschiede in der UV-Strahlung zurückzuführen, da Stroh und Boden in diesem Wellenlängenbereich eine fast identische Reflexion zeigten.
6. Der Knollenertrag und die Sortierung der Kartoffeln wurden in elf Feldversuchen über vier Jahre nicht signifikant oder in einheitlicher Richtung durch Strohmulch beeinflusst.

7. Strohmulch hatte keinen konsistenten Effekt auf Beikräuter (Anzahl Beikräuter pro Fläche, Beikrautdeckung und Biomasse der Beikräuter).
8. Dass Strohmulch keinen signifikanten Effekte auf Ertrag und Unkräuter hatte, wurde hauptsächlich auf die relativ geringen Strohaufwandmengen zurückgeführt, die sich nach dem Hauptziel der Vektorregulierung richteten.
9. Das Risiko der Stickstoffauswaschung in der Nacherntephase wurde durch Strohmulch aufgrund der Immobilisierung von Nitrat-N nach der Ernte (6.8 – 7.0 kg N pro t Stroh) in zwei Experimenten vermindert; dies entsprach 18 – 34 kg NO_3–N ha^{-1}.
10. In einem Feldversuch mit einem Regensimulator auf einem 8 % abfallenden Kartoffelfeld verminderte Strohmulch die Bodenerosion um über 97 %.
11. Der Befall der Kartoffelpflanzen mit Krautfäule (*Phytophthora infestans*) wurde in fünf Versuchen an 3 – 7 Terminen bonitiert. Strohmulch hatte in keinem Versuch einen Effekt auf den Krautfäulebefall (bzgl. Fläche unter der Befallskurve), jedoch konnte in allen fünf Versuchen ein nicht-signifikanter Trend zur Krautfäulereduzierung durch Strohmulch beobachtet werden.
12. Der Befall der Ernteknollen mit der Pockenkrankheit (Sclerotien von *Rhizoctonia solani*) wurde bei 100 – 220 Knollen pro Parzelle bonitiert; der Befall wurde nicht einheitlich durch Strohmulch beeinflusst. In acht von neun Experimenten waren die Effekte nicht signifikant.
13. Die Wirkung von Strohmulch auf das Mikroklima im Kartoffelbestand wurde in einem Feldversuch gemessen. Nachts war die Luft in den gemulchten Parzellen kühler und feuchter als in den ungemulchten, tagsüber trockener und wärmer. Diese Effekte waren vier bis sechs Wochen nach dem Mulchen weniger deutlich als in den ersten zwei Wochen direkt nach der Mulchausbringung.
14. Vorteile und Grenzen der Strohmulchanwendung im ökologischen Kartoffelanbau werden diskutiert und Parameter zur Optimisierung dieses kulturtechnischen Verfahrens vorgeschlagen.

1 Introduction

In public perception, one of the most important principles of organic farming is the forbidden use of synthetically produced pesticides, distinguishing it from conventional agriculture; however, for the conception and understanding of organic farming it is more appropriate to define this farming system by its aims and practices (Lampkin, 1994). One of the aims of organic farming is to design agricultural ecosystems in a way more similar to natural ecosystems (Altieri et al., 1996). This idea includes the establishment of a permanent cover of the soil (Rusch, 1985), which can be achieved by green manuring, intercropping, mixed or relay cropping, but also by mulching the soil. Mulch in general can be defined as (dead organic) material deliberately applied to the soil as a coverage. In contrast to covering the soil with living companion plants, mulch does not show negative effects on the crop by competition. Mulching as an ancient agricultural practice in several garden and field crops (King, 1984) serves a multitude of functions, including soil erosion control and increase of soil organic matter (Jacks et al., 1955; Rowe-Dutton, 1957).

A rather unexpected effect of straw mulch is the reduction of aphid transmitted viruses (Kendall et al., 1991; Jones, 1994; Eggers and Heimbach, 2001; Heimbach et al., 2001; Heimbach et al., 2002). In potatoes, as a crop of high economic importance in organic farming (Dreyer and Padel, 1992), many plant health problems arise from the fact that the crop is propagated solely vegetatively (Schumann, 1991). These problems include aphid transmitted virus diseases that can severely reduce yields (Radtke et al., 2000).

The general aim of the thesis presented is to comprehensively describe and evaluate the application of straw mulch in organic potatoes from the perspective of both plant protection and agronomy. It is centred around effects of mulch on the currently most important potato virus disease, the *Potato Virus Y* (PVY). As this disease is transmitted by aphids, a main emphasis of this thesis is put on the effects of straw mulch on these insects.

The thesis is divided into eight chapters. After this introductory chapter, the second chapter will give an introducing and broader literature review on the subject, building the background for the following five chapters. These are presented in form of papers for international peer-reviewed journals. Chapter 3 comprises a study on the effects of straw mulch on the incidence of *Potato Virus Y* in organic potatoes (Saucke and Döring, 2004, published; see end of reference list, "[Chapter 3]"). In chapter 4, effects of straw mulch on aphid infestation of potatoes are presented (Döring and Saucke, to be submitted). The 5th chapter will then present an investigation on the underlying mechanisms involved in the effects of mulches on aphids, with the main focus on straw mulch (Döring et al. 2004). Chapter 6 deals with further agronomically important effects and functions of straw mulch in potatoes, including effects on yield, weeds, soil erosion, and nitrate dynamics (Döring et al. 2005, accepted). In chapter 7, the response of two fungal potato diseases (late blight and black scurf) to straw mulch application is investigated (Döring et al., to be submitted). Finally, chapter 8 brings together the five previous papers by a summarising discussion.

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2 Literature review

This chapter serves to give a general introduction for the following experimental studies (chapter 3 to 7) and is separated into four sections. In the first section, general conditions of current organic potato growing practice are outlined. The second section deals with one of the most important virus disease of potatoes, PVY. It builds the background for the first two papers (Saucke & Döring, 2004, chapter 3; and chapter 4), which describe the effects of straw mulch on PVY and its vectors. In order to give a better understanding of chapter 5, the third section will then consider concepts of aphid host finding behaviour and the effects of mulches on this behaviour. In the last section, introducing chapter 6 and 7, agronomic and pedological aspects of straw mulch applications are presented.

2.1 Practice of organic potato growing

This section aims to outline the special features of organic potato growing in the temperate zones. In organic farming, potatoes have a high economic importance and value, especially when sold directly to the consumer (Dreyer and Padel, 1992). The peculiarities of organic potato farming mainly concern plant protection, rotational design, preparation of seed tubers, and weed control.

From the problems experienced during organic potato production, plant protection issues are by far the most important (Lampkin, 1994). Late blight, caused by the fungal pathogen *Phytophthora infestans* (Montagne) de Bary is seen as the most important disease in ware potatoes (Dreyer and Padel, 1992; Tamm et al., 1999). Other pests and diseases that regularly cause high (economic) losses in organic ware potatoes are the fungal diseases black scurf (*Rhizoctonia solani* Kühn), early blight (*Alternaria solani* Ellis & Martin), and silver scurf (*Helminthosporium solani* Durieu & Montagne); the bacterial diseases soft rot or black leg (*Erwinia carotovora* Jones), and common scab (*Streptomyces scabies* Thaxter); the insects Colorado potato beetle (*Leptinotarsa decemlineata* Say) and the larvae of click beetle species (*Agriotes spec.*); and the potato cyst nematodes *Globodera rostochiensis* Wollenweber and *G. pallida* Stone (Möller et al., 2003).

The rotation design and placement of the potato crop in the rotation plays a key role in organic potato growing. One of the most important functions of rotational design is the prevention of crop diseases and pest outbreaks (Freyer, 2003). *E.g.*, increasing the potato cropping frequency to one third of the rotation leads to an average yield decline of 15% in the long term, mainly due to nematodes (Möller and Kolbe, 2003). But also other pests and diseases benefit from shorter cropping breaks, such as potato wart (*Synchytrium endobioticum*), soil borne late blight (from oospores), and the soil borne nematode-transmitted *Tobacco Rattle Virus*. For seed potato production it is recommended to limit the maximal cropping frequency to 20%, *i.e.* once in five years (Möller and Kolbe, 2003). Following a survey in Britain from 1986, on most organic farms the potato is grown less than once every four years (Lampkin, 1994). Favourable precrops improve the soil structure, leave the soil friable and with a high content of easily degradable organic matter; therefore, legumes are recommended as precrops to potatoes (Dreyer and Padel, 1992; Möller and Kolbe, 2003). While some grain legumes were observed to be of variable value for the following potato crop, grass-legume mixtures (leys) are assessed to be the optimum precrop for a high yield response (Möller and Kolbe, 2003). The comparison of one year *vs*. two year grass-clover leys showed variable results.

Before planting the potatoes, presprouting (= chitting; also see section 2.2.3) is recommended for organic ware potato growing (Meinck, 1998); the major objective of this measure is to escape in time from late blight by earlier plant development (Dreyer and Padel, 1992). Therefore, presprouting usually increases and stabilises the yield level, leading to a 12–28 % yield increase in years when vegetation is terminated early by *Phytophthora infestans* (Karalus and Kainz, 2003; Möller, 2003b). Presprouting is also recommended as a control measure against the damage caused by early *Rhizoctonia solani* infections (Focke, 1952, Karalus and Kainz, 2003).

Weed control in organic potato growing is mostly done by 1) (chain-)harrowing and re-ridging (once to) twice between planting and emergence, and 2) subsequent cultivations and re-ridging when plants are larger (Lampkin, 1994). Besides weed control, ridging also serves to break up soil crusts that impede the aeration of the soil, to build a stable ridge with high volume for potato roots and tubers and to prevent greening of tubers (Kainz, 2003). Machines used for weeding are reviewed by Kainz (2003). Often, high levels of weeds occur later in the season, following the late blight infection that drastically reduces competition for light, water and nutrients exerted by the potato plant; high weed levels at harvest can impede the harvesting process and therefore cutting of haulm and weeds or sometimes hand weeding are done before harvest.

The potato crop is propagated vegetatively by seed tubers. In organic as well as conventional agriculture, the production of seed tubers differs from the production of potatoes for human consumption or industrial use. The peculiarities of seed potato production mainly refer to the required narrow size limits and the control of tuber transmitted virus diseases (Böhm, 2003).

2.2 The Potato virus Y pathosystem

This section deals with the currently most important virus disease of potatoes, the *Potato virus Y* (PVY). It starts with an outline of the disease biology and epidemiology, will then consider the economic importance of PVY for (organic) potato growing, and finally give a brief overview of selected regulation measurements.

2.2.1 Biology and epidemiology of PVY

The classic concept of plant diseases is represented by a triangle of host, environment and pathogen (Van der Plank, 1968; Agrios, 1988); this disease triangle can be expanded by a fourth factor, human interference (Kranz, 1996). Understanding virus diseases of plants, however, requires taking into account a further element, the vector, which is defined by its function to transmit the virus: It acquires the pathogen and transmits it from an infected plant to uninfected plant (Radcliffe and Ragsdale, 2002). In insect-vectored plant viruses – unlike, e.g., fungus-transmitted viruses – the behaviour of the vector further increases the complexity of the pathosystem (Nemecek, 1993).

The potato (*Solanum tuberosum* L.) is host for at least 37 virus and viroid diseases, of which eleven display a broader geographic distribution (Stevenson, 2001). Currently, in Europe the most important and dominant potato virus is the *Potato virus Y* (PVY) (Weidemann, 1988; Derron and Goy, 1990; Sigvald, 1992; Rongai and Cerato, 1997; Reschke, 1999; Ruiz de Arcaute et al., 2002; Rasocha et al., 2003). The world wide distributed PVY is a species of the family *Potyviridae*, whose members have flexuous particles ("rods") of 650–900 nm length and 11–15 nm diameter; the genome consists of single strand RNA. The genus *Potyvirus* is the largest of the family with 91 species and 88 tentative species (Hull, 2002).

Transmission of PVY is experimentally possible by mechanical inoculation (sap transmission), and also contact transmission has been reported for some isolates; in the field, however, the only relevant mode of PVY transmission is transmission by aphids (Homoptera: Aphidoidea) (Beemster and De Bokx, 1987; Stevenson, 2001). At least three factors can be distinguished that are required for a successful virus transmission (Nemecek, 1993): (1) the presence of vectors at a susceptible stage of plant age, quantitatively expressed as vector abundance (2) the (quantitatively varying) ability to transmit the virus (vector propensity) and (3) the appropriate behaviour of the vector: the aphid probes or feeds on an infected plant, moves to an uninfected one and probes or feeds again.

PVY is vectored non-persistently (Matthews, 1992); this means that the time for acquisition from infected plants and for transmission to uninfected plants is very short: a few seconds of probing are sufficient for the vector to acquire or transmit the virus (Bradley, 1954), because the virus is not acquired from the phloem but from epidermal cells. The virus is carried at the distal part of stylets (Bradley and Ganong, 1955; Wang et al., 1996; but see Martín et al., 1997) and a helper component is necessary in PVY transmission (Blanc et al., 1998). Although apterous (=wingless) aphids are able to transmit PVY, most PVY spread is caused by alate (=winged) aphids (Broadbent and Tinsley, 1951; Nemecek, 1993). Following acquisition of PVY, the infectivity of the vector decreases already within approximately 1 h and is mostly lost after only a few hours (van Hoof, 1980; Katis and Gibson, 1985). The transmission probability is decreased by increasing the length of the acquisition or inoculation period (Bradley and Rideout, 1953).

The ability to transmit PVY is dependent on the virus strain (Bawden and Kassanis, 1947), the aphid species (Bawden and Kassanis, 1947; van Hoof, 1980; van Harten, 1983; Sigvald, 1984; Boiteau et al., 1988; De Bokx and Piron, 1990; Derron and Goy, 1990; Collar et al., 1998; Halbert et al., 2003) and on the aphid biotype (Singh and Khurana, 1987).

Aphids are not able to distinguish hosts from non-host plants before having landed on the plant and briefly (5 - 60 s) probing the leaf by setting their rostrum (labium) onto the leaf surface (Hennig, 1963). Because of the short time required for PVY acquisition and transmission, many aphid species that do not colonise potatoes but probe on potato as a non-host are able to transmit PVY. The majority of PVY vectors belong to species that do not colonise potato (Katis and Gibson, 1985; Piron, 1986; Harrington and Gibson, 1989; Heimbach et al., 1998). Most PVY vectors are members of the family Aphididae; tested aphid species of other families (Anoeciidae, Drepanosiphidae, Lachnidae) were not found to be able to transmit PVY (Harrington and Gibson, 1989). The polyphagous green peach aphid (*Myzus persicae* Sulzer) is the most efficient vector of PVY (*e.g.*, Beemster and De Bokx, 1987; Sigvald, 1992). However, since vector abundance and probing behaviour also determine the spread of the virus, other species may be more important in a particular situation in the field. For example, *Brachycaudus helichrysi,* a non-coloniser of potato, has been shown to contribute to a similar or higher degree to PVY spread than *M. persicae* (Harrington and Gibson, 1989).

Following the infection of the plant by a vector (primary infection), the virus is transported from cell to cell through plasmodesmata (Hull, 2002); after reaching the phloem, it is carried from the leaves to newly formed tubers (Zobelt, 1998). Infected tubers systemically infect the whole plant when they are used as seed potatoes (secondary infection). Plants grown from PVY infected tubers develop virus strain specific symptoms. Infection with PVY^{N} (tobacco veinal necrosis or new strain) induces weak yellow-green mosaic on the potato leaves, whereas the PVY^{O} strain (original) leads to black-brown spots on the underside of leaves (Beemster and De Bokx, 1987; Radtke et al., 2000). Severe infection with PVY in susceptible varieties can lead to leaf drop (Bawden, 1943). In 1980, a new sub-strain of PVY^{N}, the PVY^{NTN} (TN from tuber necrosis) was found in Hungary. This pathogen rapidly spread all over Europe (Duvauchelle and Kerlan, 1996; Cerato et al., 1997; Tomassoli et al., 1998). It causes necrotic rings on the tuber, rendering tubers unmarketable even as ware potatoes. Other strains like PVY^{C} and PVY^{Z} do not play an economically important role in Europe (Radtke et al., 2000). PVY displays an extraordinarily high genetic diversity (Blanco-Urgoiti et al., 1998; Dedic et al., 2003) and also recombinations of different strains have been found (Glais et al., 2002).

An important feature of plant-virus interactions is the fact that the susceptibility of the potato to the virus declines over time with increasing physiological age of the plant (Hunnius, 1977). This was termed "age resistance" or "mature plant resistance" (Sigvald, 1985; Kegler et al., 1993; Andersson et al., 2002).

The host range of the PVY mainly comprises solanaceous species (tobacco, pepper, potato, egg-plant), but also many weed species from other families like *Chenopodium album* L., (Chenopodiaceae), *Sonchus arvensis* L., *Taraxacum officinale* Weber ex Wiggers (Asteraceae) and *Euphorbia helioscopia* L.(Euphorbiaceae) have been shown to be PVY hosts (Schwarz, 1959; Stollberg, 2000). However, PVY sources other than potato plants are regarded not to be relevant for the empidemics of PVY in potatoes (Carter and Harrington, 1991).

For the development of appropriate control strategies of plant diseases it is crucial to know which factors are determining the disease spread in time and its distribution in space. A large number of studies was therefore directed to the understanding of PVY epidemiology. It was found that in years with high aphid abundance during virus susceptible stages of the potato crop, the incidence of PVY was high in harvested tubers; so, the relative contribution of spring flight was seen to be larger than that of summer flight (Rieckmann & Zahn, 1998). Nemecek et al. (1995) showed with a calibrated simulation model that PVY dynamics are largely dependent on the initial inoculum y_0 (*i.e.* percentage infected seed). Regarding the spatial distribution of PVY in potato fields, virus incidence was demonstrated to rapidly decrease with increasing distance from the infection source (Gregory and Read, 1949); in this study the percentage of plants infected with PVY decreased by a factor of >10 within the first 2.25 m distance from the infection source in three out of four years. Similar observations were made by Singh et al. (1984). They found that no infection with PVY occurred beyond distances of 2.4–4.8 m from the infection source. Cherif and Hattab (1994) determined the percentage y of PVY infected potato plants as $y=13.55/x^2+0.68$, with x being the distance in meters from an infection strip.

2.2.2 Economic background

Plant virus diseases can cause severe yield losses (Oerke et al., 1994; Bos, 1999). While primary infection of potatoes with PVY does not cause significant yield reduction, plants grown from PVY infected seed tubers (secondarily infected plants) yield from 14 to over 80 % less than uninfected plants (Köhler and Klinkowski, 1954; Arenz and Hunnius, 1959; Borchardt et al., 1964; Jotoff, 1971; Wenzl, 1980; van der Zaag, 1987; Radtke et al., 2000). The yield decrease is dependent on the virus strain and the variety (Winiger and Bérces, 1974). Despite the high variability of the yield response to virus infection, in agricultural practice and extension often a rule of thumb value of 50 % yield reduction in virus infected plants is largely accepted, *i.e.* 0.5 % yield reduction per percent virus infected seed tubers in the field.

In order to ensure high quality seed for ware potato growers, in many countries seed potato certification schemes have been established that define upper limits of infection levels for certified seed potatoes (Hunnius, 1972; Shepard and Claflin, 1975). There are a number of certification grades or levels, with higher levels having lower tolerance of virus infection. Initially, potatoes are made virus free using meristem culture and virostatica in the laboratory (Kassanis, 1957; Hunnius, 1977). Subsequent generations are produced in the field, with decreasing certification grades. The continuous use of uncertified seed potatoes year by year usually leads to a quick accumulation of virus infections and corresponding yield decline.

The differences between the production of seed potatoes and ware potatoes mainly concern plant protection, and here principally virus control (see 2.2.3). Further extra costs in seed potato production include fees for the breeder and for certification, and higher costs for seed; these peculiarities of seed potato production result in a higher price for certified seed than for ware potatoes (Uhlmann, 1985). For Germany, the current price difference has been calculated by Lübbertsmeyer (2004) to be around 150 € t^{-1} for the seed *selling* organic producer, with a price ratio (seed : ware) of 1.5. For seed *buying*, the difference and ratio are greater (ca. 300 € t^{-1} and 2.1, resp.). In the conventional sector, the price ratio regarding seed buying was between 1.4 and 2.0 in the 1960´s and increased in the 1970´s (range 1.5-4.1) (Uhlmann 1985). Although the available amount of certified seed does not only vary with the yield level but also with the highly variable virus infection (Table 2.1), the seed potato price varies less from year to year than the ware potatoes price (coefficient of variation calculated from Uhlmann, 1985, p.47).

The high price of certified results in (1) the avoidance of the purchase of certified seed and instead the use of own uncertified seed from last year´s production (saved seed); for example, the ratio of certified seed to all seed used was 35-38 % in the early 1980´s in Germany (Uhlmann, 1985); (2) the development of a black market for uncertified second generation seed potatoes (Uhlmann, 1985). Due to these uncertainties, economic calculations for seed potato production are difficult.

In the organic sector, an important aim is to minimise the reliance on conventionally produced seed, including seed potatoes. At first, due to the low availability of organically grown certified seed potatoes (Böhm, 2003), the principle of self-sufficiency concerning seed could not fully be maintained, and organic growers who wanted to use certified seed were largely dependent on conventional seed potatoes. With the growing organic market and increasing specialisation, however, the use of conventional seed for organic growers was restricted (in 1996) and has been finally forbidden (from 2004 on) in the European Union. The total organic seed potato area in Germany was 300 to 350 ha in 2001, equalling about 1.6–1.9 % of the total seed potato area (Böhm, 2003). Since the organic sector has been growing for several years (*e.g.*, AGÖL, 2001) and organic potato production is expected to continue to grow in the EU (Tamm et al., 2004), the demand for organic seed potatoes will presumably continue to rise.

Table 2.1: Rejection rates of seed potatoes and percentage of virus infections caused by PVY in Germany and Czechia, ordered by year of publication

Region or country	ha	nr. of years	% decertified[e] of seed potato lots			% of viroses caused by PVY	Reference
	mean		min	median	max	mean	
Hannover[a]	4 861	5	6.4	8.4	10.1	n.m.	Körner (1975)
Weser-Ems	489	5	-	1.8	-	n.m.	Wetzel and Franken (1975); Hesse (1975)
Bayern	85	7	3.5	5.8	14.4	n.m.	Veeh (1976)
Germany	17 603	10[d]	3.3	7.3	16.6	n.m.	Uhlmann (1985)
Hannover	n.m.[c]	19	1.1	4.5	41.1	ca. 95	Reschke (1999)
MeVo[b]	4 541	10	0.4	2.0	19.6	88.8	Kürzinger and Kürzinger (2001)
Czech Rep.	5 370	4	4.9	6.6	23.7	(main)	Rasocha et al. (2003)
Hessen	219	1	-	4.9	-	n.m.	Schnabel (2004)

a: "Geschlossene Anbaugebiete" (contiguous areas of seed potato production)
b: MeVo: Mecklenburg-Vorpommern;
c: n.m. not mentioned
d: 1974-1983
e : rejected seed potatoes (Z) or downgrading of higher levels

2.2.3 Approaches to the control of PVY

Several strategies of PVY control and potato virus management in general have been published and repeatedly reviewed (Schuster, 1946; Hunnius, 1977; Loebenstein and Raccah, 1980; Zitter and Simons, 1980; Weidemann, 1988; Khurana and Garg, 1998; Radcliffe and Ragsdale, 2002). Many of the practices of PVY control were already known in the 18th century as tools against the degeneration diseases of potato ("curl") (Bagnall, 1991). However, the currently available solutions for practical application are still limited. In this section, selected approaches relevant to the presented studies will be briefly reviewed. Measurements to control PVY comprise (1) the general genetic (varietal) resistance to the virus; (2) the removal or reduction of inoculum (infected plants or seed) by the use of certified seed, roguing, or placement of the field far from infection sources; (3) the management of temporal coincidence of plant susceptibility with vector occurrence by presprouting or early haulm destruction; (4) the management of plant nutrition; approaches that interfere with (5) the vector itself (geographical distribution, abundance and reproduction); and with (6) interactions between vector and virus (acquisition and transmission) and with (7) interactions between vector and plant (host finding, settling).

(1) Resistance to PVY. Varietal resistance to the virus is one of the most important and most successful approaches in virus control (Nemecek et al., 1995). As sources of resistance many wild *Solanum* species are used in the breeding, *e.g.* from *S. stoloniferum* or *S. andigenum*. Resistance to PVY is either based on extreme resistance (like in the variety 'Bettina') where virus transport is prevented by the death of infected plant cells; or on quantitative resistance (like in 'Grata'), where reduced disease incidence in the field, lower virus concentration, or weak symptoms were observed (Kegler et al., 1993; Schenk, 1993). Currently, 68.5 % of the 200 German officially listed potato varieties have high or very high resistance to PVY, and only 6.0 % are susceptible or very susceptible varieties. Similarly, in 2002, 60.5 % of the German seed potato area (total 14,838 ha; Bundessortenamt, 2003) was planted with highly or very highly resistant varieties, and 9.0 % with susceptible or very susceptible varieties (own calculations, data Bundessortenamt, 2003). However, genetic resistance is endangered by resistance break down (Van der Plank, 1968; Fraser, 1985; Anonymus, 1987). PVY displays a high genetic diversity (Blanco-Urgoiti et al., 1998) and the ability of recombination between different strains (Glais et al, 2002). Examples for resistance break-down can be observed in the case of the new aggressive virus strains PVY^{NTN} or PVY^{N}-Wilga. Also, it was shown that transgenic pathogen derived resistance to PVY can be overcome by several isolates of PVY (Schubert et al., 2002). Another draw-back of varietal resistance is the breeders´ difficulty of combining it with other traits, like processing quality or resistance to other pests and diseases; for the (organic) farmer, these traits as well as consumer preference may be of greater immediate importance than virus resistance (Möller, 2003a). Finally, Leifert (2004) states that seed potato growers are reluctant to grow (new) highly virus resistant varieties because in this case ware potato growers can use their own seed potatoes longer and purchase less certified seed.

(2) Reduction of inoculum. The usage of certified seed is a further very successful strategy to reduce virus infection levels in potatoes (Pieper et al., 1930; Radcliffe and Ragsdale, 2002). This was recently demonstrated in India when potato virus incidence dropped considerably after advances were made in the establishment of official seed potato certification schemes (Khurana, 1998). A problem associated with the certification of seed is the low number of tubers tested. This results in a relatively large confidence interval around the officially diagnosed percentage of infection. For instance, assuming a Poisson distribution and the case of 10 % infection in certified seed (= threshold in Germany) among the usual 100 tubers tested per 3 ha, the "real" infection level is greater than 15 % with a probability of 5 %.

Roguing, *i.e.* the removal of obviously infected plants from the field, is a common and important measure to reduce virus incidence in potatoes (Weidemann, 1988; Hattab et al., 1994; Nemecek et al., 1995), especially for organic growers. However, there are several practical aspects which are a constraint for efficient implementation. New PVY strains like PVY^N-Wilga display no or only very weak symptoms on above-ground parts of the crop (Radtke et al., 2000) and do not only make roguing extremely difficult but can be seen as a consequence of roguing because of the selection of symptomless strains. Already in the 1950´s, when the PVY^N strain occurred first in Europe, a lack of symptoms with this strain was observed (Weidemann, 1988). Symptoms may also be masked by high levels of nitrogen (Wenzl and Reichard, 1973). Moreover, roguing is very labour intensive (Schramm, 1974) and expensive (Kainz, 1998). Efficient roguing requires skilled personnel and certain weather conditions (absence of direct sunlight). Finally, the gap created with the removal of the infected plant can lead to higher attractiveness of the neighbouring plants to vectors (see section 2.3) and increased weed infestation.

The local or regional placement of the field can further contribute to inoculum reduction, namely by the isolation of seed potatoes from generally more heavily infected ware potato stands. "Contiguous" seed potato areas therefore proved to be more successful in certification rates than smaller areas interspersed with ware potatoes (Körner, 1975).

A main strategy in virus control is the choice of the geographic area for seed potato production: virus diseases occur less in areas of higher latitudes, at higher altitudes, and at the wind-swept coasts (Wetzel and Franken, 1975), where natural vector abundance is low. Therefore, within Europe, regions have been specified for seed potato production.

(3) Temporal coincidence of susceptibility and vector appearance. Presprouting ("chitting" or "pre-germination") is done by warming up the seed and exposure to light. This procedure breaks the dormancy and results in earlier plant development, usually by 10-14 days. Presprouting is frequently used by organic farmers to reduce yield losses due to late blight caused by *Phytophthora infestans* (Möller, 2003b) and was shown to increase tuber yield (Karalus, 1998a; Möller, 2003b). With presprouting, mature plant resistance to virus diseases is achieved earlier and can therefore protect against (late) infections and reduce virus incidence (Sigvald, 1985; Andersson et al., 2002). However,

in certain years with early vector activity, presprouting may increase the risk of early virus infection due to the earlier emergence, and is therefore not generally recommended (Karalus, 1998b; Böhm, 2003).

A strategy similar to presprouting is the shortening of the susceptible period of the crop at the end of the growing season by early killing of vines (haulm destruction) (Krätzig, 1975) or by green crop lifting (Fittje and Böhm, 2002; Böhm and Fittje, 2002). In organic farming, the late blight infection can been seen as a natural haulm destruction agent, helping in reducing late virus infections. With these measures, whether deliberately controlled or not, timing relative to vector phenology is essential for the success of virus reduction. A major disadvantage of shortening the growing period of the crop is yield reduction; in the case of early green crop lifting a yield reduction by 22.4 % was observed (Fittje and Böhm, 2001), which appears relatively high even for seed potatoes.

(4) Plant nutrition management. In several cases, plant nutrition management was demonstrated to influence virus infections in potatoes, but effects were not significant in other studies (Klapp, 1951; Krüger, 1951; Proeseler, 1963; Birecki et al., 1964; Hunnius, 1967). Rieckmann (2000) points out that high levels of N lead to masking of virus symptoms and make roguing more difficult. Following these investigations, the general recommendation for seed potato production is a moderate nitrogen level (Böhm, 2003) and a high level of phosphorus (Brouwer, 1976).

(5) Direct control of vectors. The killing of the vector by insecticides (aphicides) for control of non-persistent viruses has continuously been subject to criticism since the 1950s (Broadbent, 1957; Radcliffe and Ragsdale, 2002). Nevertheless it is still a regularly used and frequently recommended measure in conventional agriculture (Kürzinger, 2000; Rieckmann, 2000, p. 153). The most important drawback of aphicides is their low effectiveness against non-persistent viruses (Smith and Webb, 1969; Rieckmann, 1991; Boiteau and Singh, 1999), because the time for virus acquisition and transmission is too short for the pesticides to kill the vector (Shanks and Chapman, 1965; Zellner, 1998). This is particularly true for systemic pesticides (Perring et al., 1999). Thus, the widespread replacement of contact insecticides in conventional practice by systemic ones is regarded as the main reason for the present dominance of PVY, whereas the persistently transmitted PLRV and others are largely under insecticidal control. Perring et al. (1999) reviewed field experiments on PVY control with insecticides and found successful control in six studies and nine studies where insecticides failed to control PVY.

Furthermore, problems arise by the fast development of resistance of vectors to the active ingredient (Ffrench-Constant et al., 1987; Devonshire, 1989; Rongai and Cerato, 1994; Rongai et al., 1998; Robert et al., 2000), although vector species that are not colonising potato are less prone to insecticide resistance build-up. Other reasons for criticism include the possible increase in probing activity (Thieme and Heimbach, 1998; but see Collar et al., 1997) or mobility (Nemecek, 1993; but see Boiteau and Osborn 1997) after pesticide application; environmental costs (Pretty et al., 2000); lethal effects on honey bees (von der Ohe et al., 2004); and the risk of residues in tubers that failed certification and are sold for human consumption. Although newly developed aphicides with different modes of action, more rapid degradation in the tuber or in the soil might possibly display these problems to a lesser degree, they are not an option for organic growers.

(6) Interference with virus transmission. An approach that impedes the transmission of the virus is the application of mineral oils (Külps and Hein, 1972; Vanderveken, 1977). At present however, this approach is not practised in seed potato production. The use of Neem oil, as a botanically derived substance allowed in organic farming, has been studied in Northern Spain with "partial control" of PVY (Handizi and Legorburu, 2002).

(7) Interference with host finding and settling of the vector. As aphids are known to colonise the crop from the field margin (Moericke, 1941), large square fields with a low margin/area ratio are recommended for seed potato production (Böhm, 2003). Some further vector related approaches like the use of trap crops (Difonzo et al., 1996; Thieme et al., 1998), nets (Handizi and Legorburu, 2002) and alarm pheromones (Nault and Montgomery, 1977; Hille Ris Lambers and Schepers, 1978) are not relevant to this study and are reviewed elsewhere (see above). They have not yet reached the state of widely adopted practices.

From the quick mode of transmission of PVY and its epidemiology it can be reasoned that approaches interfering with early phases of the host finding behaviour of the vector are likely to be efficient for PVY control. This has not only been concluded from simulations with an epidemiological model of PVY (Nemecek, 1993), but has also been confirmed in many studies in numerous other crops where so-called reflective surfaces were successfully used for vector control. These are reviewed in section 2.3.2.2.

2.3 Mulches and aphid behaviour

Straw mulch can considerably reduce aphid infestation and virus infection in potatoes (chapter 3 and 4). A series of experiments was conducted to elucidate the mechanisms involved in straw mulch effects on alate aphids. To give a broader background to the experiments presented chapter 5, a short review on host finding behaviour of aphids is followed by a section summarising the effects of various mulch materials on aphids and aphid-vectored viruses.

2.3.1 Host finding behaviour of aphids

Host finding in winged aphids is a complex behaviour that is closely linked with migration and the function of dispersal. Accordingly, the reviews by Kring (1972) (*Flight behaviour of aphids*) and Robert (1987) (*Dispersal and migration*) both include the process of host finding, landing, and probing. The classical and often-cited concept of host finding behaviour in aphids was developed by Moericke (1955). It distinguishes four behavioural stages each corresponding to a certain behavioural "mood" (*Stimmung*; motivation) and is shown for the example of a host-alternating aphid species.

(1) After the last moult and wing hardening and before take-off from the winter host plant, the aphid is in a resting mood (*Ruhestimmung*); this phase before take-off is also referred to as teneral period.

(2) Environmental conditions (low wind speed, above-threshold air temperatures, no precipitation) allow the aphid to enter the flight mood (*Flugstimmung*). With take-off, the winged aphid is positive phototactic and shows a positive response to UV wavelengths. Rising from the leaf into the sky, the flying aphid is lost to the observer´s eye after several metres, but there is strong evidence that aphids fly over longer distances once they have taken off, given favourable flight conditions. This period is called distance flight or migration flight (*Distanzflug*).

(3) In the following attacking flight (*Befallsflug*; and corresponding attacking mood = *Befallsstimmung*), the aphid repeatedly lands and probes on plants. Short, so-called trivial flights from plant to plant are made during this stage. Nemecek (1993, p. 71) estimated that the probable distance of trivial flight bouts is about 13 m, with 20 % of flights terminating within 1 m from take-off.

(4) The behavioural sequence is terminated by the settling period (settling mood = *Ansiedlungsstimmung*) in which first larvae are deposited on the (summer) host plant. According to Moericke´s model, the four moods overlap in time.

A different concept of aphid host finding behaviour was developed in a series of flight chamber studies with alate *Aphis fabae* by Kennedy and coworkers (references see below). A pair of two antagonistic behavioural categories, *flight* and *settling*, was proposed. In contrast to the model of Moericke, Kennedy´s concept implies a flexible balance of the behavioural sequences with a reversible order instead of a more or less fixed four-step cascade. In this model, the strength of the *flight* response is measured as the rate of climb against an artificial air current or as the flight duration. The strength of the *settling* response is measured as the duration of stay on a presented leaf or substitute, or by a set of ordered categories: "0 probes", "1 probe", ">1 probe", "going onto the underside of the leaf", and "larviposition" (Kennedy & Booth 1964). Settling and flight mutually affect each other by two mechanisms, called "antagonistic depression" (inhibitory after-effect) and "antagonistic induction" (excitatory after-effect) by Kennedy. The results of Kennedy and coworkers can be summarised in a model with six important behavioural processes (Fig. 2.1).

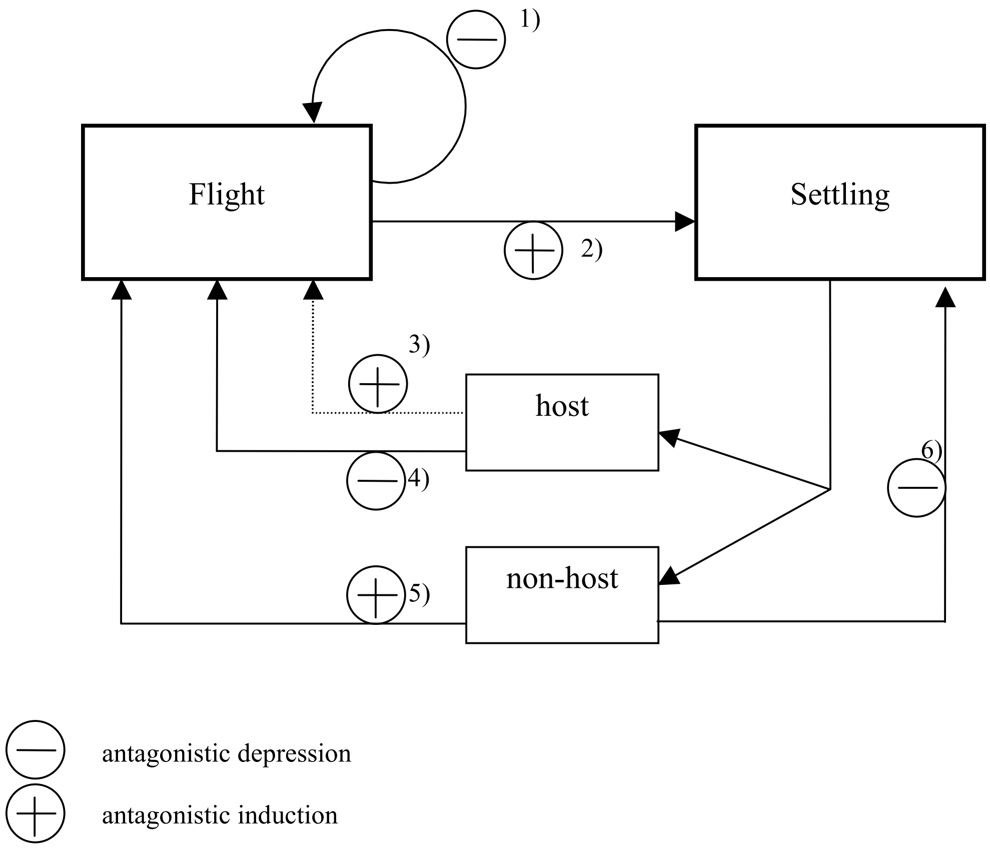

Fig. 2.1: Mutual interaction of flight and settling response in alate *Aphis fabae.* For explanation of (1)-(6) see text.

(1) The longer the duration of the flight, the weaker becomes the rate of climb, i.e. the flight response (Moericke, 1955a; Johnson, 1958; Kennedy, 1966: fig. 1, group A).

(2) The longer the flight, the stronger becomes the settling response (excitation of settling by flight, antagonistic induction). (Kennedy, 1965: fig. 3 and 4; Kennedy and Booth, 1963: fig. 3; Kennedy and Ludlow, 1974).

(3) After the (first) landing(s) on a host leaf presented, flight is resumed (rebounce of flight) with an increased *maximum* strength compared to the time before landing (antagonistic induction) (Kennedy, 1966: fig. 4 A). Also in the field, aphids having found a host depart from the host in large proportions (Kennedy et al., 1959a; Kennedy et al., 1959b).

(4) After host contacts, the flight response, measured as the *average* or *minimum* rate of climb, becomes weaker than directly before landing on the host (inhibition of flight by settling, antagonistic depression) (Kennedy, 1965: fig. 4).

(5) With a non-host contact, the flight response is increased (similar to 3) (antagonistic induction) (Kennedy, 1965: fig. 4; Kennedy, 1966: fig. 6).

(6) A series of prior landings on a non-host leaf weakens the settling response to host leaves (Kennedy and Booth, 1964: fig. 4). However, Klingauf (1976) found a stronger settling response of *Acyrthosiphum pisum* on hosts after short non-host than after host contact.

As the repeated alternation between probing and short flights is of paramount importance for the transmission of plant viruses, it has been subject to extensive research. Many stimuli and environmental conditions have been found to influence flight (Broadbent, 1949), and landing or probing response during the "attacking flight", including tactile (Hennig, 1963), visual (see below) and olfactory cues. Olfactory stimuli, such as isolated plant volatiles, have been shown to play a role in host finding of aphids (Chapman et al., 1981), but these are considered to be less important, mainly because alate aphids are obviously not able to discriminate between host and non-host prior to probing, i.e. they alight "quite indiscriminately" on host and non-host (Kennedy, 1950; Kennedy et al., 1959a; Kennedy et al., 1959b).

2.3.2 Effects of visual stimuli on aphids

2.3.2.1 Primary colour effects on aphids

The first study suggesting that aphids react to visual stimuli was published by Moore (1937) on aphid response to coloured pesticides and dusts. However, in this investigation, the alighting response was not observed but only the number of aphid colonies, and colour (wavelength) was not separated from light intensity. Evidence for colour perception in aphids was then given by Moericke (1950). The number of probings on differently coloured and illuminated paper was highest in orange, yellow and green, and low on red and blue; aphids that came from a coloured paper to a grey one differed in their probing activity on the grey paper, with the highest response (on grey) after blue, suggesting a successive contrast effect. With a series of field experiments Moericke (1955) demonstrated the effect of colour stimuli on aphid landing. Pure yellow without ultraviolet showed the strongest attraction to alatae, with orange, yellow-green and green following, whereas the aphids responded with low landing rates to red, blue, purple, white, grey and black. Already small areas (2.6 cm diameter) of yellow are attractive to aphids. On large (2.4 m x 2.4 m) yellow cloth, aphids landed preferably at the margin (outer 10–20 cm) whereas fewer alighted in the centre. The attractiveness of the green-yellow wavelength band (around 550 nm) was confirmed with respect to approaches by walking (Hodgson and Elbakhiet, 1985), flying (Hardie, 1989), and probing (Pelletier, 1990). There was even a positive effect of yellow light on reproduction and survival on artificial diets (Auclair, 1967). Because of the attractiveness of yellow to landing aphids, yellow traps are widely used for aphid monitoring (Moericke, 1951; Rieckmann and Zahn, 1998) and suggested for control (Budnik et al., 1996).

Differences between aphid species in their colour preference have been demonstrated on numerous occasions. *Hyalopterus pruni* Geoffroy was more strongly attracted to yellow when the colour was unsaturated, i.e. when mixed with white lead; this was not the case with *Aphis fabae* Scopoli

(Moericke, 1969). *Rhopalosiphum padi* L. was more attracted to green than to yellow whereas *Sitobion avenae* F., *Rhopalosiphum maidis* Fitch and *Schizaphis graminum* Rondani preferred yellow (Kieckhefer et al., 1976).

Besides the attractiveness of yellow, landing aphids are known to be generally repelled by shorter wavelengths (Moericke, 1955a; Kennedy et al., 1961). However, the response of aphid landing to white, which usually has a high short-wave reflexion, was varying (Moericke, 1962). As humans are not able to see UV, the varying UV reflexion of white across different studies may be one reason why results were inconsistent. In contrast to the repellency of short wavelengths to landing aphids, alatae in stage 2 of Moericke´s behavioural sequence (distance flight) are attracted to UV. This was interpreted as a change in the aphid´s "mood". In field experiments the attractiveness or repellency of white may therefore also reflect different moods of individual aphids.

2.3.2.2 Secondary colour effects: Mulches and other backgrounds

Mulch can be defined as dead material deliberately applied to the soil as a coverage. Although traditionally the word is used for organic material (including straw), in horticultural crops, the term "mulch" currently includes and is often focussed on plastic material. In any case, mulches form a background to the crop that is optically different from the plant and the soil. So, apart from the direct or primary optical influence of the plant on the aphid described in the previous section (2.3.2.1), a secondary effect of the background on landing can be supposed.

Indeed, different mulches have been reported to have a repellent effect on aphids as virus vectors and to reduce virus incidence in different cultures. The materials applied included aluminium, and white, black or coloured (blue, green, silver, and gold) plastic mulch (Smith et al., 1964; Dickson and Laird, 1966; Johnson et al., 1967; Adlerz and Everett, 1968; Wolfenbarger and Moore, 1968; Heathcote, 1968; Jones and Chapman, 1968; Smith and Webb, 1969; Fusco and Thurston, 1970; Kring, 1970; George and Kring, 1971; Shands and Simpson, 1972; Nawrocka et al., 1975; Daiber and Donaldson, 1976; Eulitz, 1977; Wyman et al., 1979; McLean et al., 1982; Kuroli and Erdélyi, 1990; Jones, 1991; Liburd et al., 1998; Brust, 2000).

Nearly all colours or materials tested show some degree of reduction in the number of alate aphids caught in yellow water traps in the mulched *vs.* in the unmulched treatments. The highest efficiency was consistently found with aluminium, often reducing alatae that landed in traps by over 90%. In line with this result, it was found that aluminium mulch reduced the incidence of aphid vectored plant viruses in various crops to a high degree. Black mulch material also lead to decreased aphid infestation on the crop, aphid landing rates or virus incidence, but usually with a lower reduction efficiency and with a high variability of the efficiency between the studies.

Green living plants as background were also efficient in reducing aphid catches. (González and Rawlins, 1968; Smith, 1976) and the number of colonising *Brevicoryne brassicae* L. on Brussels sprouts (Smith, 1976). Heathcote (1968) found that the effect of mustard or barley grown between sugar beet stecklings on aphid infestation of beet plants depended on the aphid species. While *Aphis fabae* was always most abundant in open beds, *i.e.* without cover crop, the response of *Myzus persicae* was inconsistent over two years. Infection with *Beet Yellow Virus* was reduced by both barley and mustard cover compared to beets without cover crop. Interestingly, virus reduction was higher with cover crops than with aluminium strips between sugar beet rows over three years. In cabbage, undersowings with subterranean clover (*Trifolium subterraneum*) lead to the reduction of aphid populations (Lehmhus, 2001). Bigler et al. (1995) found that over four years, aphid populations on corn were reduced when the corn was drilled into a rotovated band of a grass-clover meadow or green rye by an average of 80 % (meadow) and 49 % (rye), compared to conventional drilling into completely uncovered soil.

In the investigations on the use of mulch for protection of plants from virus diseases, three features were often stated: (1) The higher the percentage of soil covered with mulch the higher the efficiency (e.g., Adlerz and Everett, 1968; Lehmhus, 2001) (2) The efficiency of the mulch decreases over the growing season along with the increasing canopy of the plant (e.g., Brust, 2000). (3) The comparably high costs of mulching are only economically justified in high value crops or when severe losses occur regularly due to virus diseases (*e.g.*, Brust, 2000).

The experience that various green living mulches reduced infestation of several insect pest species, including aphids on cruciferous crops, was explained by Finch with the 'appropriate/inappropriate landing' theory (Finch, 1996; Finch and Kienegger, 1997; Finch and Collier, 2000; Finch and Collier, 2003). It is based on the observation that phytophagous insects land indiscriminately on green surfaces, but usually avoid landing on brown surfaces like soil. While host contact (appropriate landing) leads to settling, an inappropriate landing, *i.e.* on a non-host plant, is followed by the insect flying off the plant. In this case, the host searching process is either repeated or the insect "simply leaves the area" (Finch and Collier, 2003, p. 132).

The considerations set forth in the previous two sections lead to the question if straw mulch reduces aphid infestation by direct repellency in a short-wavelength band; by camouflage; or by the 'appropriate/inappropriate landing' mechanism. This will be discussed in the chapters 5 and 8.

2.4 Agronomic effects of straw mulch in potatoes

For the potential adoption of straw mulch application in practice, it is crucial to know how the main agronomic parameters, especially yield, are affected. This is presented in chapter 6. The following review will first describe the abiotic requirements for potato growing, then consider the properties and use of cereal straw and finally summarise known effects of mulches on the soil.

2.4.1 Abiotic requirements for potato growing

The potato is susceptible to frost, heat and drought (Schütt, 1972); damage to tubers occurs below –1 to –3°C (daily mean temperature at 2 m height) and above 29°C, damage to vines below –1.5°C; the optimum temperature for yield is around 17°C (Kolbe, 2003). The optimal water availability is about 60–80 % of water holding capacity (Kolbe, 2003). Compared to other crops (e.g., rye), potatoes display only weak yield responses to changes in soil texture. Potatoes can be grown over a broad soil texture range and negative effects on yield were only observed on very heavy clay soils or very sandy soils (Kolbe, 2003). On lighter sandy soils, sufficient water availability is crucial. However, many quality parameters are negatively affected when potatoes are grown on clay soils and benefit under sandy soil conditions. Regarding soil structure, potatoes have a low tolerance to soil crusting and require a friable and loose soil, that quickly warms up.

2.4.2 Yield, properties and use of cereal straw

For temperate climate conditions, Boguslawski and Debruck, (1977) report yields of cereal straw between 4.0 and 8.0 t ha^{-1} with 5.0 t ha^{-1} on the average; winter wheat and rye showed higher straw yields (5.5 t ha^{-1} DM) than summer wheat and winter barley (4.5 t ha^{-1} DM). According to yield increases during the last few decades, more recently published figures are well above these values, with 7.0 to 9.0 t ha^{-1} for winter wheat (Kübler, 1994). For organic farming, Stöppler (1989) reports wheat straw yields between 5.2 and 7.2 t ha^{-1} from experiments with 20 varieties over three years. Straw is mainly used for animal husbandry (as bedding material, to bind urine and dung, and as occasional fodder). In a survey for Germany in 1974, three quarters of the total straw were used for this purpose. Further 20 % were incorporated into the soil, and 5 % were burnt (Boguslawski and Debruck, 1977). Currently, straw burning on the field is forbidden by law.

Cereal straw contains low levels of N (0.4% of dry matter), but has a high C content, resulting in a high C/N ratio ranging from 85 (summer barley) to 100 (wheat and rye). K levels of cereal straw range between 1.0 % of DM (in wheat) to 2.5 % of DM (in oats), and P contents are between 0.07 and 0.17% of DM (Boguslawski and Debruck, 1977). More than 90 % of straw is organic matter, with cellulose around 45 % and lignine 15-18 % of dry organic matter. A further important component of straw is SiO_2 with 3-5 % of dry matter.

Physical and structural properties of straw from 55 winter wheat varieties and 25 summer wheat varieties were measured by Heyland (1953). On the average, he found that the total length of straw was 95 cm in winter wheat and 89 cm in summer wheat, with a total weight of 1.6 g and 1.3 g and a diameter of 3.5 mm and 3.1 mm, respectively (figures calculated as means over 2 years). More recently, Stöppler (1989) reported total plant lengths of 90-110 cm for organically grown winter wheat. Straw has a high water holding capacity, capable of holding an amount of water around 200 % of its own weight (Heyland, 1953).

2.4.3 Effects of straw mulch on the soil

2.4.3.1 Soil physical properties

Many investigators have found increased soil moisture under straw mulch (Albrecht, 1922; Albrecht and Uhland, 1925; Torstensson, 1931; Turk and Partridge, 1947; Verma and Kohnke, 1951; Pereira and Jones, 1954). Absolute differences in the moisture content between mulched and unmulched soil (top 30 cm) range from 1 to over 6 weight-% and are typically around 2 to 3 %. Increased soil moisture under mulch has mainly been attributed to two causes: (1) increased infiltration (Duley and Kelly, 1939; Ayanlaja and Sanwo, 1991), caused by interception of rain drops by mulch in turn leading to reduced soil compaction and pore sealing; (2) decreased evaporation, *i.e.* improved moisture conservation (Esselen, 1937; Russel, 1940; James, 1945; Mooers et al., 1948; Adams, 1966; Lal, 1975; Ayanlaja and Sanwo, 1991). It was found that half the effect of evaporation control comes from shading (Russel, 1940). Evaporation control increases with higher amounts of straw mulch (Russel, 1940; Verma and Kohnke, 1951), but the increase in the effect from *additional* amounts of straw decreases, *i.e.* already light applications of straw are almost as effective as heavier ones (Russel, 1940).

Further reasons for increased soil moisture have been seen in weed suppression by mulch leading to lower evapotranspiration, the higher albedo of straw than of uncovered soil, leading to lower surface temperature, and increased dew formation with mulch (Jacks et al., 1955). The effect of increased soil moisture decreases with soil depth, *i.e.*, it can be observed mainly in the upper soil layers (Morita and Oguro, 1951; Adams, 1966). A further important condition that influences the effect of mulch on soil moisture is the amount of rainfall: due to interception of the precipitation, small showers may not be saved at all, so the effect of mulch intercepting the rain and causing its evaporation before reaching the soil is highest with low rainfalls (Russel, 1940).

Soil temperature has been found to be stabilised under straw mulch in many studies. Straw mulch increased soil temperatures in winter (Heuser, 1930), during the night (Musso, 1932) or minimum soil temperatures (Singh et al., 1988), but decreased average and maximum soil temperatures in summer by 1 to 6 K, mostly by 2 to 3 K (Hays and Smith, 1900; Albrecht, 1922; Albrecht and Uhland, 1925; Heuser, 1930; Torstensson, 1931; James, 1945; McCalla and Duley, 1946; Opitz, 1948; Lal, 1975; Singh et al., 1988; Caliskan and Caliskan, 2002). The decrease in soil temperature was higher under heavier than under lighter mulch (Scott, 1921; McCalla and Duley, 1946; Lal, 1987). While the straw is darkening during the season, temperature differences between mulched and unmulched soil decrease (McCalla, 1944).

Straw mulch has been demonstrated to reduce run-off and soil erosion (Duley and Kelly, 1939; Borst and Woodburn, 1942a; Borst and Woodburn, 1942b; Dawson, 1946; Adams, 1966; Ayanlaja and Sanwo, 1991; Nill and Nill, 1993). Mechanisms involved in reduction of soil erosion by straw mulch are reduced run-off; reduced velocity of run-off; reduced rill formation (Borst and Woodburn, 1942a);

higher infiltration (Jacks et al., 1955); and reduced impact of falling raindrops on the soil and therefore reduced break-up of soil aggregates (Jacks et al., 1955). Borst & Woodburn concluded from a series of experiments with straw mulch that "the flow of water over the surface was of much less importance than raindrop impact as an erosion-causing factor, and that elimination of the latter was the main contribution of the mulch." (Borst and Woodburn, 1942b).

2.4.3.2 Soil chemical properties

In some early studies, nitrate levels have been found to be lower in soil under mulch than in unmulched soil (Scott, 1921). When straw (at 8t/acre) was removed in autumn and replaced in spring over three years, also lower nitrate levels were found in a silt loam soil under mulch (Albrecht, 1922). In addition, indirect effects of straw mulch may alter the nitrate content of the soil during the growing season. Higher soil moisture or decreased soil temperature may both increase or decrease the soil nitrate content. When straw is incorporated into the soil, soil nitrogen may be locked up due to the high C/N-ratio of straw (immobilisation) (Jacks et al., 1955; Thurston, 1997; Cheshire et al., 1999). On arable farms, straw is often incorporated into the soil after the harvest of the cereals.

Long term application of straw mulch was shown to increase the organic matter content of the soil (Thurston, 1997), but also in the short term, *i.e.* following one year of straw application, a slight increase by 0.2 %-points caused by straw mulch was observed (Verma and Kohnke, 1951).

2.4.3.3 Soil biota

Various soil biota have been reported to benefit from the application of straw mulch. For example, earthworm populations have been shown to increase under straw mulch (Thurston, 1997). Mulch protects the soil from excessive desiccation and "provides earthworms with readily available food" (Jacks et al., 1955). As a consequence, earthworms may decrease the straw cover by feeding on it. In soil samples (0-23 cm) from straw mulched and unmulched potato fields (Krüger, 1952) counted individuals of the soil fauna; although it was not stated how much straw was applied and sampling dates differed between treatments, it may carefully be concluded from this study that the number of collemboles, diplopodes, and dipteran larvae was higher, but the number of enchytraeids and mites was lower under straw than in bare soil.

Summarising the effects of straw mulch on soil, mulching leads to (1) increased soil moisture; (2) decreased and stabilised soil temperature; (3) drastically reduced run-off and soil erosion (4) moderate increase in organic matter content; (5) varying effects on soil nitrate levels, depending on soil temperature and moisture; as well as immobilisation of nitrogen after straw incorporation (6) increased numbers of earthworms and some other soil biota.

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Summary

Potato virus Y (PVY) is transmitted non-persistently by winged morphs of many aphid species and is a main problem in seed potato production. In order to evaluate the potential of straw mulch applications (4-5 t ha^{-1}) and presprouting on PVY reduction, small scale organically managed field experiments were carried out in Northern Hessen, Germany, over 3 yr. In all years mulching significantly reduced aphid infestation on leaves as well as PVY incidence in tubers. For the effect of presprouting the temporal coincidence of two factors was crucial - crop emergence and aphid flight activity. Presprouting decreased PVY incidence when in the phase of early crop emergence aphid spring flight activity was low, but increased it, although not significantly, when prominent aphid flight peaks occurred in this critical period. Straw mulch was most effective when vector pressure was concentrated early in the year acting as a PVY protectant for young plants. In later growth stages its effect declined gradually with increasing ground coverage of the crop. Combined mulching and presprouting had a synergistic, complementary effect on reduction of PVY incidence. In an on-farm experiment in 2001 scaling up the area mulched stepwise from 100 m² to 900m² consistently kept aphid infestation at reduced levels.

Key words: Aphids, seed potatoes, vectors, PVY, presprouting, chitting

3.1 Introduction

The world wide distributed *Potato virus Y* (PVY, family *Potyviridae*, genus *Potyvirus*) is currently regarded as one of the main problems in seed potato production (Stevenson 2001). The virus is vectored non-persistently, mainly by alate aphids, with species-dependent vector efficiency and most PVY vectors belonging to species that do not colonise potato (Broadbent & Tinsley 1951; Kennedy *et al*. 1962; Harris 1977; van Hoof 1980; Katis & Gibson 1985; Matthews 1992; Heimbach *et al*. 1998). Several strategies of PVY control and potato virus management in general have been published and repeatedly reviewed (Hunnius 1977; Zitter & Simons 1980; Maelzer 1986; Khurana & Garg 1998), however, practically relevant non-chemical approaches appear to be limited (Radcliffe & Ragsdale 2002).

Presprouting (=chitting) which is frequently used by organic farmers to reduce severity of late blight (*Phytophthora infestans* (Mont.) de Bary) is also reported to contribute to earlier mature plant resistance to virus diseases resulting in reduced virus incidence, particularly in cases of late inoculations (Beemster 1972; Beemster 1976; Sigvald 1985). However, presprouting may also increase the risk of early virus infections due to earlier exposure to vectors and has therefore not been generally recommended.

Straw mulch has been well studied in reducing aphid infestation and virus incidence in several crops, such as barley (Kendall *et al.* 1991), faba bean (Heimbach *et al.* 2002), lupins (Jones 1994), and rape (Heimbach *et al.* 2000; Heimbach *et al.* 2001). Furthermore, straw mulch as an organic and relatively cheap material is also on-farm available in the required quantities.

Objectives of this study were (1) to quantify the straw mulch effect on vectors and virus incidence in organic potatoes; (2) to investigate if straw mulch is efficient and mechanically applicable on a larger scale and (3) to evaluate the combined effects of mulching and presprouting, where mulch could possibly protect the highly susceptible early phase of crop establishment.

3.2 Materials and Methods

3.2.1 Field experimental design

All field experiments were conducted on the experimental farm of the University of Kassel at the locations Hebenshausen and Neu-Eichenberg (Germany) *c.* 30 km NE from Kassel, 220 to 250 m above sea level, with 7.9°C mean air temperature, 619 mm yearly precipitation and clay-silt soils on loess.

3.2.1.1 Small scale experiments

From 2000 to 2002 four small scale field experiments (Expt A-D, Table 1) were set up with a plot size of 12 rows (9 m) by a length of 11 m (in 2000) or 9 m (2001-2002) in a randomised complete block design with four replications. Varieties used were Christa (very early maturing) in all 3 yr, and Nicola (intermediate maturity) in 2002, both being highly susceptible to PVY (Bundessortenamt 2003). In order to minimise interplot interaction the plots were arranged in a line approximately across the main wind direction (Thresh 1976). Row direction was parallel to this line. Planting density was 3 tubers m^{-1} within rows and 0.75 m distance between rows for all varieties. Plots were separated by bare soil strips, 5m from each other and 2.5-3 m from neighbouring crops (peas in 2000 and potatoes var. Rosella in 2001 and 2002, certified seed). The seventh row (i.e. one of the two centre rows) was planted with presprouted infector plants with a high percentage of PVY (85% in 2000, 100% in 2001 and 2002; var. Produzent), whereas the remaining seed potatoes were virus free (in Christa, Expt A-C, number of tubers tested see table 2) or contained 6% PVY (Expt D, Nicola) (Thresh 1976).

The treatments were as follows: (1) mulching with wheat straw, applied by hand at 5t/ha (Christa) and 4t/ha (Nicola), respectively, shortly after emergence; (2) presprouting (=chitting), by exposing seed tubers to light and higher temperature (approx. 3 to 6 K difference in daily means) in white open plastic trays in the greenhouse for 2 to 4 wk before planting; this lead to the emergence of the plants 8 to 10 days before the non-presprouted crop, as well as earlier flowering and senescence; (3) the combination of mulching and presprouting (not included in Expt A); (4) an unmulched and unpresprouted check.

Dates for planting, emergence, mulching and harvest are summarised in Table 1. In all years weed control was done two times before mulch application with a rotary finger wheel hoe with ridging discs. Estimated weed cover did not exceed 20% in any year or plot before haulm death caused by late blight.

Table 1: *Details of experiments*

Experiment	A	B	C	D	E
Factors/treatments	Mulch & Presprouting	Mulch x Presprouting	Mulch x Presprouting	Mulch x Presprouting	Mulched area
Variety	Christa	Christa	Christa	Nicola	Marabel
Year	2000	2001	2002	2002	2001
Planting date	19.4.	23.4.	10.4.	15.+20.5.	10.5.
Mulching date in presprouted	-	18.5.	16.5.	3.6.	12.6.
Mulching in non-presprouted	19.5.	28.5.	26.5.	10.6.	-
Date of harvest	13.7.	26.7.+27.7.[a]	14.8.+16.8.[a]	23.9.+24.9.[a]	2.9.
Plot size (m * m)	9 * 11	9 * 9	9 * 9	9 * 9	10 * 10, 20 * 20, 30 * 30
Seed tubers tested before planting	167	224	293	100	100
Seed tubers PVY positive (%)	0	0	0	6	0
Harvested tubers per row grown in greenhouse for test	9	33	20	20	pooled, see text
ditto per plot	99	363	220	220	pooled
Harvested tubers tested per plot [b]	74 ± 5	323 ± 39	200 ± 12	181 ± 24	pooled

[a] harvest of mature tubers occurred blockwise on two dates; haulms had already died back completely before harvest.

[b] mean ± standard deviation; the difference between the number of harvested and the number of finally tested tubers per plot is caused by losses due to non-sprouting eyes; the number of tested tubers was statistically independent from treatment and row.

3.2.1.2 Effect of area mulched (scaling up experiment)

In 2001, an on-farm, large scale field experiment (Expt E, table 1) with two replications was set up with the highly PVY-resistant var. Marabel (0% PVY at planting). Straw mulch was applied with a Kverneland Round bale chopper, KD 807, at *c.* 3.5t ha^{-1} twelve days after crop emergence. Treatments were (a) area mulched on 100 m², (b) 400 m², (c) 900 m²; (d) 20 m long unmulched separation strips between mulched plots.

3.2.2 Harvest and yield measurement

Harvesting was done by hand in Expt A and E and with a Samro Spezial potato lifter with cleaning drum in Expt B, C and D. No yield measurement was done in Expt A. Tubers were harvested in Expt B, C and D from the complete plot length (9 m) and all twelve rows. However, yield analyses are based on seven rows, as the two rows adjacent to the infector plants and the outer rows were disregarded in order to reduce edge effects. In Expt E in each plot tubers were harvested from two rows from the centre of the plots on 3.30 m length. Harvested tubers were sorted with a Schmotzer shaking-grid-type potato sorter, partitioning the lots into three fractions (<35 mm, 35-65 mm, and >65 mm in Expt B and E; and <35 mm, 35-55 mm, and >55 in Expt C and D).

3.2.3 Virus diagnosis and vector monitoring

In Expt A, at harvest one tuber per plant from nine randomly selected plants per row was collected for virus tests. In Expt B, C and D, from each of the 12 rows, 33, 20 and 20 tubers, respectively, were selected blindly from the middle-sized fraction after sorting (Table 1). Virus diagnosis was done by DAS-ELISA (non-strain-specific, polyclonal PVY antisera from BIOREBA, Switzerland) with leaf sap obtained from eyes cut after harvest and grown in aphid free greenhouse chambers (Casper & Meyer 1981; Torrance 1992). The average number of tested tubers per plot are summarised in Table 1. In Expt E, the harvested tubers were pooled into two fractions (mulched and unmulched, with 478 and 434 tubers tested respectively).

In all years background vector flight activity was monitored with two yellow water traps after Moericke (1950, 1955), which were placed on bare soil at each end of Expt A-D. Sticky black nets on aluminium frames (Heimbach et al. 2002) of 0.5 m by 0.5 m (mesh size 7.7 mm by 4 mm, water proof insect glue Soveurode®, Witasek, Austria) were exposed *c.* 10 cm above the plant canopy in the centre of plots in presprouted Christa plots (Expt B) from 22 to 25 May 2001. In Expt A to D the percentage of aphid infested leaves was determined weekly to fortnightly by inspecting 99 leaves per plot, i.e. nine randomly selected leaves per row in 11 rows and counting the leaves infested by aphids (Broadbent 1948). The same method was applied on 5 July 2001 in Expt E with 300 leaves per plot (75 leaves in four rows). Vector identification followed Taylor (1984) and Heie (1980, 1982, 1986, 1992, 1994, 1995).

3.2.4 Statistical analysis

Statistical calculations were done with SAS v6.12 (Anon., 1990, 1994). All analyses of variance followed GLM procedures. For data within plots (aphid data over time; and virus and yield data over rows, i.e. over distances from infector source) Repeated Measure Analyses were used (Milliken & Johnson 1992; Anon., 1994). There were no significant interactions between rows (i.e. the repeated factor) and the treatments or blocks. Therefore virus and yield data were averaged over rows for each plot. An unbalanced data set caused by the destruction of one plot in 2001 (Expt B) was analysed with LSMEANS procedure. All percentage values were arcsin-square-root-transformed before further statistical analysis.

3.3 Results

3.3.1 Virus and vectors

3.3.1.1 Vector phenology and species composition of vectors

In 2000, vector activity peaked distinctly in mid of May and remained on low levels throughout the following summer. 2001 was characterised by overall low numbers of alatae and a moderate peak at the end of June. In 2002, spring flight peaked later than in 2000 but was of unusually long duration (Fig.1).

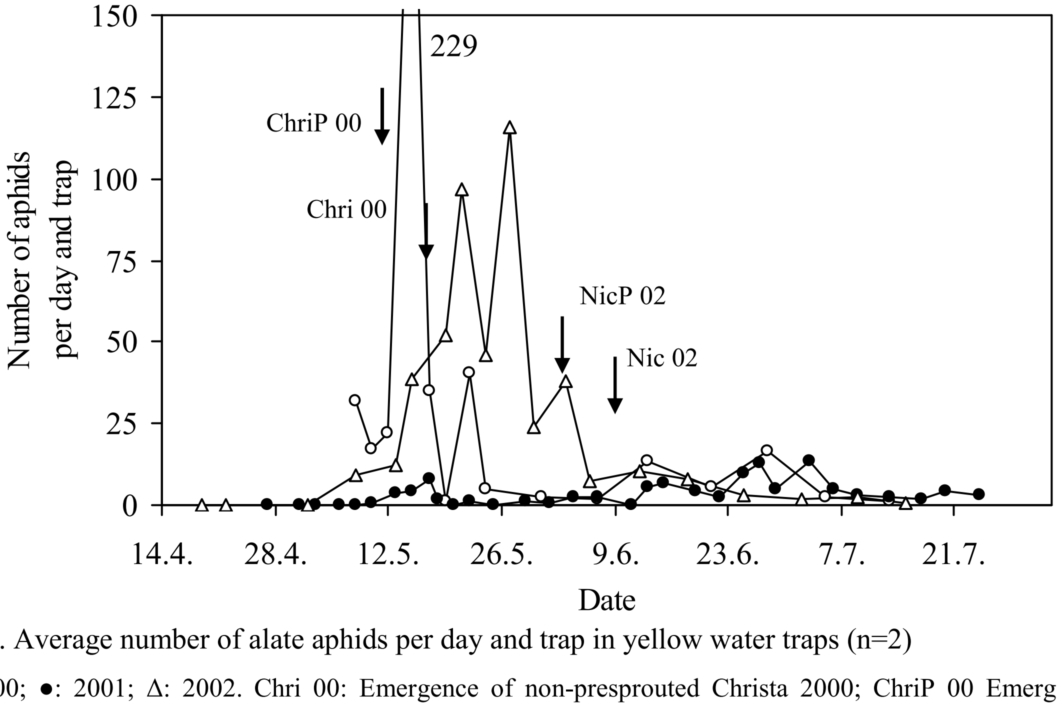


Fig. 1. Average number of alate aphids per day and trap in yellow water traps (n=2)

○: 2000; ●: 2001; Δ: 2002. Chri 00: Emergence of non-presprouted Christa 2000; ChriP 00 Emergence of presprouted Christa 2000; Nic02: Emergence of non-presprouted Nicola; NicP 02: Emergence of presprouted Nicola.

The species composition of alate aphids caught in yellow water traps is summarised in Table 2. Spring flight was dominated by *Cavariella aegopodii* and *Brachycaudus helichrysi* in May in 2000 (46.7% and 32.8 % respectively) and in 2002 (41.5% and 44.2% respectively), but not as clear in 2001. Based on the whole trapping period per year, further dominant taxa were *Aphis fabae* group, other *Aphis* ssp. (including *Aphis nasturtii*) and *Brevicoryne brassicae*. Following Harrington & Gibson (1989) *B. helichrysi*, *Aphis* ssp., and *Myzus persicae,* due to their combined vector potential and dominance are regarded as most important vectors in this study.

Table 2: *Aphid species composition from yellow water traps in three years: dominance for each year and dominances for date of maximum aphid catch; both calculated from two pooled traps*

Trapping Period	Whole trapping period in			Peak flight period in		
Year	2000	2001	2002	2000	2001	2002
Date	8.5.-20.7.	27.4.-31.7.	8.4.-9.8.	15.-17.5.	27.-29.6.	27.-30.5.
Total number of aphids (=100%)	4421	571	2912	1972	51	699
Number of aphids per day and trap				493.0	12.8	116.5
Species with >20 individuals in total catch (dominance in %)						
Acyrthosiphum pisum (Harris, 1776)	0.7	4.2	0.2	0.0	0.0	0.0
Aphis fabae group (see Brown, 1989)	2.2	23.5	8.0	1.8	35.3	2.7
Aphis ssp. L., 1758	3.4	18.4	7.0	1.7	21.6	1.3
Brachycaudus helichrysi (Kaltenbach, 1843)	24.8	13.8	33.0	32.8	19.6	44.2
Brevicoryne brassicae (L., 1758)	9.7	8.1	0.2	0.1	3.9	0.0
Capitophorus hippophaes (Walker, 1852)	0.4	0.0	0.0	0.2	0.0	0.0
Capitophorus similis van der Goot 1915	0.7	0.2	0.2	0.2	0.0	0.3
Cavariella aegopodii (Scopoli, 1763)	32.3	5.4	35.2	46.7	7.8	41.5
Cavariella pastinacae (L., 1758)	5.4	0.0	1.8	4.9	0.0	2.9
Cavariella theobaldi (Gillette et Bragg, 1918)	6.0	0.5	1.7	7.8	0.0	1.6
Cryptomyzus galeopsidis (Kaltenbach, 1843)	0.3	1.4	0.9	0.1	3.9	0.9
Dysaphis ssp. Börner, 1931	1.6	0.9	0.9	0.5	0.0	0.3
Hyperomyzus lactucae (L., 1758)	3.2	1.2	1.1	1.5	0.0	1.1
Macrosiphum euphorbiae (Thomas, 1878)	0.3	0.5	0.3	0.0	0.0	0.3
Metopolophium dirhodum (Walker, 1849)	0.8	2.8	0.5	0.0	2.0	0.0
Microlophium carnosum (Buckton, 1876)	0.0	0.7	1.3	0.0	0.0	0.0
Myzus persicae (Sulzer, 1776)	2.0	5.8	0.9	0.4	0.0	0.1
Phorodon humuli (Schrank, 1801)	2.0	0.0	0.8	0.7	0.0	0.1
Rhopalosiphum padi (L., 1758)	0.2	0.2	0.5	0.1	0.0	0.0
all other species	3.9	12.4	5.5	0.7	5.9	2.7

3.3.1.2 General effects of straw mulch and presprouting

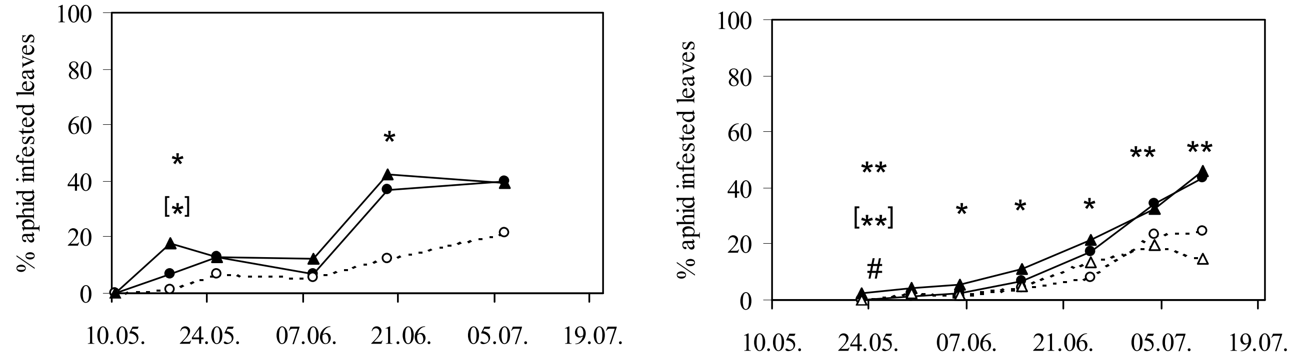
In all three years straw mulch reduced PVY incidence significantly in the four small-scale experiments (Table 3). Differences in the overall virus level between years corresponded to varying background vector activity measured with yellow water traps (Fig. 1). On black sticky nets, straw mulch did not reduce landing rates significantly (Wilcoxon´s U-test). The percentage of aphid infested leaves was reduced by mulching in Expt. A on two out of the six sampling dates, in Expt. B throughout almost the whole season (six out of seven dates) and in Expt. C and D on mid season dates (three and one respectively out of five dates) (Fig. 2).

Table 3: *PVY incidence in harvested tubers in small-scale experiments*

Experiment	A[a]	B	C	D
Variety	Christa	Christa	Christa	Nicola
Treatment / year	2000	2001	2002	2002
PVY incidence (%)				
Untreated Check	70	18	73	60
Mulching with straw	34	12	55	50
Presprouting	73	9	50	66
Mulching and Presprouting	-	6	41	59
Factorial Analysis[b] (angle-transformed data)				
Unmulched Mean	0.993	0.036	0.908	0.922
Mulching Mean	0.621	0.029	0.764	0.834
P (Mulching)	<0.001	0.004	0.006	0.027
Unpresprouted Mean	0.993	0.039	0.933	0.915
Presprouted Mean	1.019	0.027	0.738	0.841
P (Presprouting)	ns	<0.001	0.001	ns[c]
Interaction Mulch *Presprouting	-	ns	ns	ns
Error df	6	8	9	9
SED	0.051	0.002	0.041	0.033
Relative reduction efficiency of treatments in %				
df	3	6	7	7
Average mulching efficiency	-51	-33	-20	-14
SE (Mulching efficiency)	4.9	7.7	6.7	4.1
Average presprouting efficiency	+5	-51	-28	+17
SE (Presprouting efficiency)	7.7	6.0	5.3	8.6

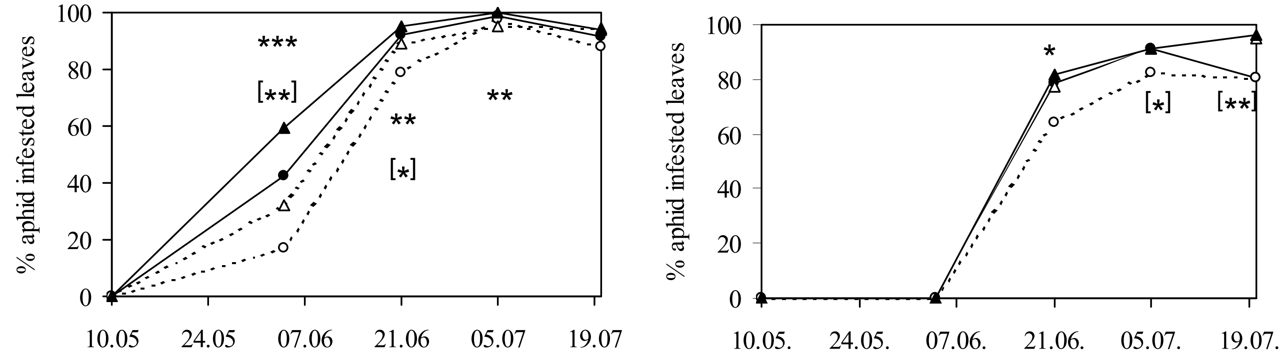
[a] Expt. A not factorial; [b] LS Means in Expt. B; [c] P=0.053

Presprouting significantly reduced PVY incidence in two cases (2001 and 2002 in the very early variety Christa), but increased it in the other two cases (2000 in Christa and 2002 in the later variety Nicola; Table 3; not significant). Early in the season, the percentage of aphid infested leaves was significantly higher in presprouted than in not presprouted plots (Fig. 2). In none of the two-factorial experiments with mulching and presprouting (B, C and D) there was a statistically significant interaction between treatments regarding PVY (Table 3).



a) Christa 2000

b) Christa 2001



c) Christa 2002

d) Nicola 2002

Fig. 2. Percentage of aphid infested leaves over time in four experiments; ●: check; ○: mulched; ▲: presprouted; Δ: mulched and presprouted; stars indicate significant mulching effects, stars in brackets significant presprouting effect; # significant interaction between treatments; significance level: * $p<0.05$; ** $p<0.01$; ***$p<0.001$.

3.3.1.3 Temporal aspects: Treatment effects and vector phenology

PVY reduction by mulching was highest in 2000 (Table 3) when vector activity was concentrated early in the year (Fig. 1). In contrast, mulching in 2002 was less effective with only 20% (Christa) PVY reduction (Table 3). Here vector activity relative to crop emergence occurred later and was of longer duration until the start of June (Fig. 2). Later planting in variety Nicola, postponing crop emergence and straw application (Table 1), resulted in the least PVY reduction (14%) by mulching. Straw mulch related PVY reduction was still considerably high in 2001 although most of the vector flight activity took place in the summer months and virus spread was much lower overall.

In 2000, crop emergence of the non-presprouted check occurred when the vector flight peak was already in sharp decline towards mid May and there was no significant effect of presprouting on PVY incidence. Similarly, presprouting did not significantly influence PVY incidence in Nicola in 2002, when aphid flight had already broken down at emergence of the non-presprouted crop. In 2001 when aphid flight peaked latest, PVY reduction efficiency by presprouting was greatest.

3.3.1.4 Spatial aspects

In Expt E (effect of area mulched) straw mulch reduced aphid infestation of leaves and this effect was independent from the area mulched (Fig. 3). Tubers pooled from all mulched plots in Expt E revealed 0.23% PVY, compared to 0.84% in tubers pooled from all unmulched plots. This difference was not significant (χ^2=1.53). In experiments with infector strip (A to D), PVY incidence was highest in rows adjacent to the infector plants and gradually decreased with increasing distance from the virus source, with a slight increase towards the outer rows. This effect was observed in all plots with no significant interaction with any of the treatments.

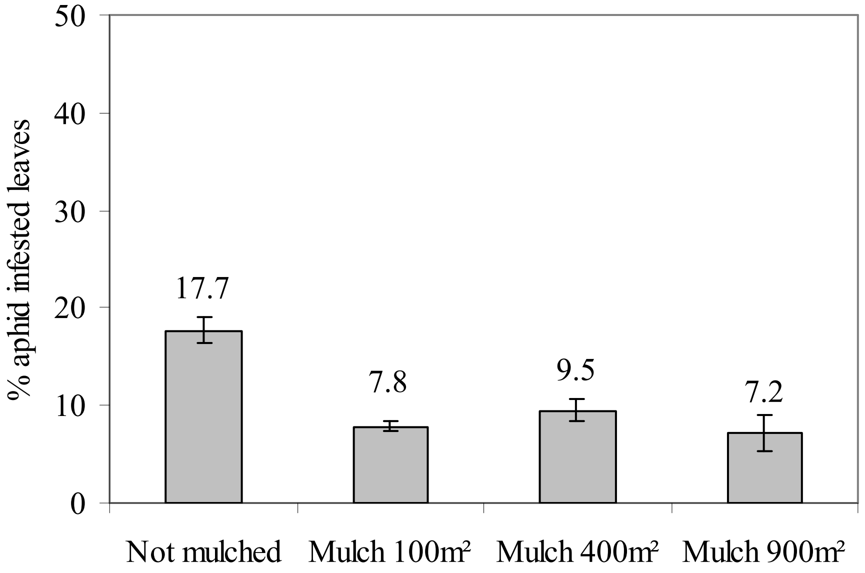


Fig. 3. Percentage of aphid infested potato leaves depending on area mulched with straw, var. Marabel, 2001, Expt E; mean ± SE; from 300 leaves per plot; mulched vs. unmulched differ at $P < 0.001$, df = 5, LSD (5%) = 3.4; areas mulched do not differ significantly ($P > 0.5$ df = 2; LSD (5%) = 7.3).

3.3.2 Yield

Total yield was not affected significantly by mulching in any of the experiments (Table 4). Presprouting increased total yield significantly in Expt B, but yield increase by presprouting was not significant in the other experiments.

Table 4: *Total yield in dt/ha in Expt B, C, D and E*

Total yield (dt/ha) / Experiment Variety Treatment / year	B Christa 2001	C Christa 2002	D Nicola 2002	E Marabel 2001
Untreated Check	321.9	142.4	143.4	431.5
Straw mulch	344.0	134.8	151.0	457.9
Presprouting	396.5	141.0	157.0	-
Straw mulch and Presprouting	405.4	140.2	167.5	-
Factorial Analysis[a]				
Unmulched Mean	359.2	141.7	150.2	-
Mulch Mean	374.7	137.5	159.3	-
Change (mulched/unmulched) in %	+4.3	-3.0	+6.0	+6.1
P (Mulch)	ns	ns	ns	ns
Unpresprouted Mean	333.0	138.6	147.2	-
Presprouted Mean	400.9	140.6	162.3	-
Change (prespr./unprespr.) in %	+20.4	+1.4	+10.2	-
P (Presprouting)	<0.001	ns	ns	-
Interaction Mulch x Presprouting	ns	ns	ns	-
Error df	8	9	9	4
SED	10.5	14.9	13.8	12.3

[a] LS Means in Expt. B & E

3.4 Discussion

Various mulch materials have been reported to reduce aphid infestation, number of landing vectors and virus incidence in several crops. The materials applied included aluminium and white, black or coloured plastic mulches. It is believed that their aphid repellency is based on the reflective properties of these materials (Kring 1964; Wolfenbarger & Moore 1968; George & Kring 1971; Shands & Simpson 1972; Zitter & Simons 1980; McLean *et al*. 1982; Simons 1982; Gibson & Rice 1989; Jones 1991). Although few studies were accompanied with quantitative spectral measurements (Kennedy *et al*. 1961; Costello 1995), landing alatae are known to be repelled by shorter wavelengths probably below 500 nm and attracted by yellow (Moericke 1950; Hardie 1989). Therefore, virus and vector reduction by straw, which appears "yellowish" at least to the human eye, is at first sight unexpected. However, apart from the direct repellency or attractiveness of different wavelengths, also further optical factors of the background such as reduction of the optical contrast between plant and soil (camouflage) play a role in the host finding process (Moericke 1955; Kennedy *et al*. 1961) and may explain straw mulch effects.

Combined effects of straw mulch applications and presprouting were consistently most efficient in reducing PVY infections in experiments with the very early variety Christa. PVY suppression by mulching was highest in the early phase of crop development and when most aphid-related infections occurred early, i.e. in spring. As the effect on vectors declines gradually according to progressing ground coverage of the crop (Adlerz & Everett 1968; Gibson & Rice, 1989; Antignus 2000; Heimbach *et al*. 2002), mulch does not protect against late vector incidence. In this stage of crop development presprouting appears to gain contributing relevance, particularly in years with low spring- but high summer vector activity. On the other hand it was disadvantageous in years with distinct aphid flight peaks at the time of early emergence, when unpresprouted plants had not emerged yet, like in the year 2000 and in exp. D with the later var. Nicola (see arrows in Fig. 1). Combined mulching and presprouting had therefore a synergistic, complementary effect on PVY reduction. From the non-significant interaction between both factors (Table 3) it can be concluded that the measures neither disturbed nor enhanced each other. With regard to practical implications combined mulching/presprouting would decrease the dependency of both single component approaches from the respective aphid phenology which is difficult to predict for seed potato growers.

The mulching effect on vectors remained high when scaling up the area mulched. Thus, feasible mechanical spreading techniques of straw into row crops with existing machinery and its application to areas approaching 1 ha, e.g. in geometric arrangements of 50 m times 200 m, appear to have a realistic perspective.

Apart from its function as a vector/virus management tool in seed potatoes the integration of mulching in organic crop rotations has several further agronomic and economic implications which need to be taken into account as follows: These effects include the reduction of soil erosion (Brandt 1997; Edwards et al. 2000) and increased water retention of the soil as well as yield increase under arid climatic conditions (Singh *et al*. 1987, Saha *et al*. 1997); however, in this study with a temperate climate and on a loamy soil with high water retention ability straw mulch effects on yield were not significant. Mulching may also be a useful management tool for nitrogen in the critical post harvest phase, where the risk of soluble N losses are of much more economic concern in organic than in conventional farming. Post harvest effects of mulch materials incorporated into the soil were studied by Cheshire et al. (1999) where the loss of soluble N was reduced due to temporary immobilisation. Possible disadvantages of using straw mulch may arise when with a wetter soil at harvest the mechanical harvesting process is impeded or must be delayed, but this was not observed in this 3 yr study.

Summarizing, the perspective of a mulching approach for PVY/vector management in organic seed potatoes appears to be promising. Adoption will depend on the optimisation of application technique, its efficacy, progresses done in the optimal timing of mulch application and mechanical weed management as well as a thorough economic evaluation including associated effects which is subject for further investigations.

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4 Effects of straw mulch on potato-colonising aphids (Hemiptera: Aphididae) in potatoes

Abstract

Aphids are important pests on potatoes, mainly due to their ability to transmit virus diseases, but occasionally also lead to economic damage by phloem feeding. Eleven field experiments were conducted over three years at two sites on organically managed farms to investigate the effect of straw mulch, applied at 2.5–5.5 t ha^{-1} shortly after crop emergence, on aphid infestation of potato leaves. The percentage of leaves infested with aphids and the aphid population size were repeatedly determined during the growing period in ten and five of the experiments, respectively, by inspecting 50 or more leaves per plot; the percentage of aphid infested leaves was significantly reduced by mulching two weeks after mulching in four experiments and later, at peak infestation in eight experiments. In two out of five experiments, aphid population size was significantly reduced by mulching. In a small scale experiment, the response of aphids landing in green water traps to varied amounts of straw (0–800 g m^{-2}) was investigated. Straw applied as a mulch patch of 60 × 83 cm under green water traps resulted in a general reduction of aphids landing in the traps compared to traps placed on bare soil. This effect was significant at application rates of 200 g m^{-2}, 400 g m^{-2}, or more, with differences among rates between 200 and 800 g m^{-2} not significant. A possible mechanism for straw mulch effects on aphids is seen in the interference with host finding behaviour.

Key words: aphids, host finding, mulch, potato, straw

4.1 Introduction

Although population densities of aphids on potatoes rarely reach levels that cause serious damage to the crop by mere phloem feeding (Metcalf et al., 1951; Radcliffe and Ragsdale, 2002), aphids are nevertheless important pests in potatoes (Guenthner et al., 1999), mainly due to their role as virus vectors (Radcliffe and Ragsdale, 2002). Several strategies for the control of aphids as virus vectors have been developed and reviewed (*e.g*. Robert, 2000). One of these approaches is the use of cereal straw as a mulch material (Jones, 1994; Heimbach et al., 2002). Particularly, it was shown that straw mulch can contribute to the control of the non-persistently transmitted Potato virus Y (PVY) in potatoes (Saucke and Döring, 2004).

It was recognised early that for assessing the spread of non-persistently transmitted viruses the population size of potato-colonising aphid species is not appropriate as a sole indicator (Broadbent, 1950; Kennedy, 1950). However, potato-colonising species are responsible for the spread of persistently transmitted viruses, with Potato leaf roll virus (PLRV) being the currently most important of these viruses. Therefore, the population size of potato resident aphid species is considered as an important additional indicator for decisions in potato virus control. Apart from aphid population size, the percentage of aphid infested leaves has been proposed early on as an appropriate tool in assessing virus spread (Broadbent, 1948). Therefore, both parameters were used in this study to assess the prospects of straw mulching for the control of virus diseases in potatoes. A further objective of this study was to establish a dose-effect relationship by characterising the effect of the amount of straw applied on the landing of aphids.

4.2 Material and Methods

4.2.1 Field experimental design

The effect of cereal straw mulching after emergence of the crop was investigated in eleven organically managed field experiments with randomised complete block designs on two farms in Germany (635 to 709 mm precipitation/year; 8.1°C mean air temperature): The experimental farm of the University of Kassel at Hebenshausen and Neu-Eichenberg, 51°23' N, 9°55' E, 220 to 250 m above sea level with clay-silt soils on loess (site A); and an arable farm, 51°28' N, 10°08' E, ca. 240 to 280 m above sea level with loamy soils (site B). For all experiments mulched and non-mulched plots were marked within existing potato fields, except for exp. 1, which was set up as a separate small-scale experiment, with plots separated by strips of bare soil. Planting and mulching dates, mulch quantities and plot sizes are presented in Table 1. Chopped straw mulch was applied by hand in exp. 1, with a Kverneland Round Bale Chopper (KD 807) in exp. 2 and 3; and with a Hawe Stable Straw Spreader in exp. 4 to 11. Further details about experiment 1 and about experiments 2 to 6 are presented in Saucke and Döring (2004) and Döring et al. (2004a), respectively.

Table 1: Details of experiments: number of replications, plot size, dates of planting and mulching, mulch quantity and number of leaves inspected per date and plot.

Exp.	Site	Variety	Year	replications	Plot length (m)	Plot width (m)	Planting date	Mulching date	Mulch quantity (t ha^{-1})	Leaves per plot	Number of leaf inspection dates
1	A	Christa	2000	3	11	9	19.4.	19.5	5.0	50	4
2	B	Christa	2002	3	30	9	5.4.	17.5.	3.5	50	6
3	B	Nicola	2002	8	25	15	8.4.	17.5.	3.5	50	5
4	A	Marabel	2003	4	18	24	17.4.	28.5.	3.0	50	4
5	B	Christa	2003	4	27.5	15	26.3.	8.5.	2.5	150[b]	7
6	B	Nicola	2003	8	27.5	30	15.4.	21.5.	3.0	50	7
7	A	Marabel	2004	4	15	13.5	2.4.	28.5.	5.0	50	7
8	A	Simone	2004	4	13.5	13.5	2.4.	28.5.	5.5	50	7
9	B	Christa	2004	4	30	9	31.3	18.5.	5.0	100	6
10	B	Nicola[a]	2004	4	20	12	19.4.	24.5.	5.0	50	7
11	B	Nicola[a]	2004	4	20	12	19.4.	24.5.	5.0	50	7

a: exp. 10: not presprouted; exp. 11: presprouted; b: 150 on the first five dates; 50 on the last two dates.

4.2.2 Aphid infestation of potato leaves

The percentage of aphid infested compound leaves was determined in weekly to fortnightly intervals by inspecting 50, 100 or 150 leaves per plot (Table 1) and counting the leaves infested by one or more aphids. Leaves were randomly chosen from the lower, middle and upper part of the plants. In addition, the aphid abundance over time was determined in five experiments (1, 2, 5, 6 and 9) by counting the number of aphids on the respective number of leaves.

4.2.3 Landing response to varied amounts of straw mulch

In order to investigate the effect of the amount of straw applied on the landing of alate aphids, a field experiment was set up on 28 June 2004 with eight levels of wheat straw (0, 100, 200, 300, 400, 500, 600 and 800 g m^{-2}) in a randomised complete block design with three replications. Dry weight of straw was determined from three samples of 50 g as 88.7 ± 0.3 %. Aphids were caught in green water traps, 15.5 cm x 21.0 cm wide and 5.0 cm high. Traps were filled with ca. 1 l of tap water and 2 ml of 25 % Tween 20® as an odourless detergent, and were placed in the centre of a straw mulched or non-mulched area of 60 cm by 83 cm. The plots were arranged in a line on a 3.5 m wide strip of bare soil neighboured by wheat on the one side of the strip and by potatoes on the other side. Plots were spaced by 90 cm of bare soil, so that the total length of the experiment was 24*(0.60+0.90) = 36 m. Aphids were collected from the traps on the 29 June 2004 within less than 20 min per block.

4.2.4 Statistical analysis

Statistical calculations were done with SAS v6.12 (SAS Inc. 1989; SAS Inc. 1990). Percentage values, such as aphid infested leaves, were arcsin-square-root transformed before ANOVA. Untransformed data are presented.

4.3 Results

4.3.1 Effect of straw mulch on aphid infestation of leaves

The most dominant aphid species was *Aphis nasturtii* (Kaltenbach) in all experiments. Other frequent species were *Macrosiphum euphorbiae* (Thomas) and *Myzus persicae* (Sulzer).

In four out of ten experiments (2, 3, 6 and 10) mulching significantly reduced early aphid infestation of potato leaves (Table 3). In three further experiments (8, 9 and 11) there was a non-significant trend of aphid reduction by straw mulch; in the remaining experiments there was either no early infestation at all (exp. 5) or low to moderate infestation (4 and 7).

Table 3: Aphid infestation of potato leaves expressed as percentage of infested leaves about two weeks after mulching; means ± standard error.

Exp.	Date	Days after mulching	Unmulched	Mulched	Relative reduction	Significance level
2	30.5.02	13	40.0 ±7.5	17.3 ±1.0	-56.7	**
3	5.6.02	19	36.5 ±4.6	16.3 ±2.2	-55.5	***
4	11.6.03	14	1.5 ±0.5	1.5 ±1.0	0.0	ns
5	20.5.03	12	0.0 ±0.0	0.0 ±0.0	0.0	(ns)
6	4.6.03	14	6.5 ±2.2	3.3 ±2.7	-50.0	*
7	9.6.04	12	12.5 ±0.5	12.5 ±3.8	0.0	ns
8	9.6.04	12	11.0 ±1.3	4.5 ±1.0	-59.1	ns[a]
9	2.6.04	15	2.0 ±0.7	0.5 ±0.3	-75.0	ns[a]
10	9.6.04	16	9.0 ±1.9	2.5 ±1.0	-72.2	*
11	9.6.04	16	9.5 ±1.5	6.0 ±0.8	-36.8	ns

a: p<0.1*: p<0.05; **: p<0.01; ***: p<0.001; ns: not significant; relative reduction calculated as the average difference between unmulched and mulched relative to level of unmulched check

Aphid infestation of potato leaves at the date of peak infestation showed a high variability between years from a minimum of 3 % to a maximum of over 99 % (Table 4). There was also considerable variability between experiments within years. Peak aphid infestation was significantly reduced by straw mulch in eight out of ten experiments. This was the case with both high and low aphid infestation levels (e.g., exp. 7 and 6, respectively); there was no significant correlation between the level of infestation and relative reduction.

Table 4: Aphid infestation of potato leaves, expressed as percentage of infested leaves at the time of peak infestation, as affected by straw mulching; means ± standard error.

Exp.	Peak date*	Unmulched	Mulched	Relative reduction	Significance level
2	2.7.02	99.3 ±0.6	93.3 ±2.5	-6.0	*
3	2.7.02	99.0 ±0.5	89.8 ±2.5	-9.3	***
4	9.7.03	38.5 ±2.1	28.0 ±2.4	-27.3	ns[a]
5	12.6.03	3.0 ±0.6	2.5 ±1.3	-16.7	ns
6	9.7.03	12.5 ±2.2	6.8 ±2.8	-46.0	*
7	7.7.04	99.0 ±0.6	74.0 ±7.0	-25.3	*
8	7.7.04	94.5 ±2.1	43.0 ±1.7	-54.5	***
9	30.6.04	53.5 ±1.0	37.5 ±3.8	-29.9	*
10	21.7.04	76.0 ±3.7	42.0 ±7.1	-44.7	*
11	7.7.04	82.5 ±3.8	71.5 ±3.3	-13.3	*

a: p<0.1; *: p<0.05; **: p<0.01; ***: p<0.001; ns: not significant; relative reduction as in table 3.

Straw mulch application caused a significant reduction of the peak population of potato colonising aphids in two out of five experiments (Table 5). In the remaining three experiments there was a non-significant trend of aphid reduction.

Table 5: Aphid peak population density (number of aphid individuals per 100 leaves) as affected by straw mulching; means ± standard error.

Exp.	Peak date	Leaves inspected	Aphids per 100 leaves		Relative reduction	Significance level
			Unmulched	Mulched		
1	19.06.00	50	36.0 ±15.3	9.3 ±3.5	-74.1	ns
2	19.06.02	50	1829.3 ±594.6	589.3 ±204.8	-67.8	ns
5	04.06.03	150	4.2 ±2.7	2.5 ±1.2	-36.0	ns
6	09.07.03	50	49.0 ±20.1	11.0 ±3.8	-77.6	**
9	30.06.04	100	337.8 ±21.5	158.8 ±33.0	-53.0	**

**: $p<0.01$; ns: not significant; relative reduction as in table 3.

4.3.2 Landing response to varied amount of straw mulch

A total of 508 alate aphids was caught in the green water traps. Straw applied as a mulch under green water traps resulted in a reduction of aphids landing in the traps; this effect was statistically significant with 200g m^{-2} and amounts equal or greater than 400g m^{-2}, but already from 200g m^{-2} on, a further increase of the straw quantity did not cause a further statistically significant reduction (Figure 1).

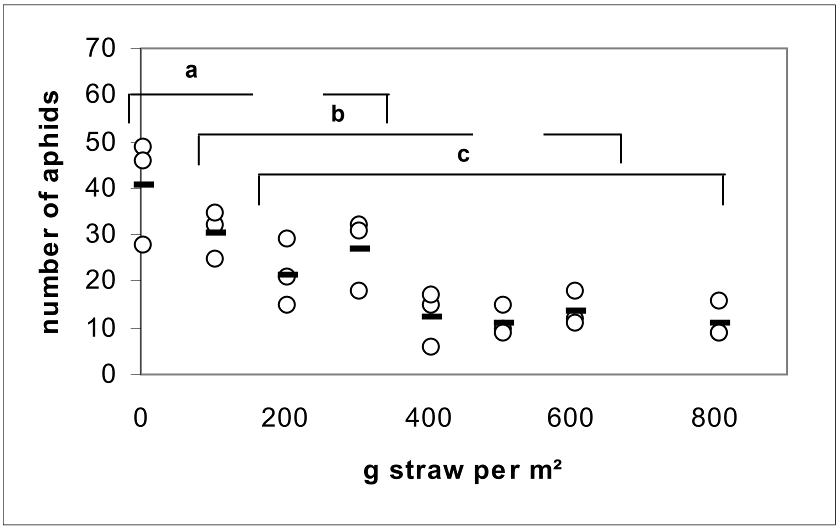

Figure 1: Effect of varied amounts of straw on the number of alate aphid individuals caught in green water traps. ○: single values; ‒ mean. Brackets and letters indicate Tukey grouping.

4.4 Discussion

Straw mulch consistently lead to reduced aphid infestation of potatoes. The effect was more marked later in the season, *i.e.* at peak infestation, than earlier, around two weeks after mulch application. Principally, several factors can be considered to be responsible for reduced aphid infestation in straw mulched potatoes, three of which we will discuss here: increased predator population or activity; alterations in plant nutritional composition; and interference with aphid host finding behaviour.

Predator hypothesis. Although the influence of predators can definitely be excluded regarding the effects of straw mulch on aphid landing, as presented in the green water trap experiment (Figure 1), they may be considered as a further factor for aphid reduction in the field (*cf.* Kendall et al., 1991). If increased predator abundance or activity were involved in the reduction of aphid infestation in straw mulched potato plots, aphid populations should display a lower population growth rate in this treatment, due to increased mortality. For experiment 1, 2 5, 6 and 9, relative growth rates were calculated, but they were neither affected significantly by mulching, nor was there a consistent trend.

Plant nutrition hypothesis. Early studies have demonstrated that straw mulch can lead to decreased levels of soil nitrate (Scott, 1921; Albrecht 1922) and therefore may cause a change in the nutritional composition of the plant, possibly a lower nitrogen content. In line with these findings, a slight yellowing of the potato plants was observed late in the season in exp. 8, and less marked in exp. 7., confirming results presented by Döring et al. (2004a). Again, aphid population growth rates should respond to this factor, but this was not the case. However, a cooling effect of straw mulch on the soil (Jacks et al. 1955), may lead to decreased mineralisation already early in the season and cause differential settling of aphids. On the other hand, plant nutrition factors were excluded in the small scale experiment with a definite reduction of aphid inflight. Concluding, it cannot be answered yet if soil-plant interactions play an additional role in the straw mulch effects on aphids in the potato crop.

Host finding behaviour. As already suggested by Kendall et al. (1991), straw mulch may interfere with the host finding process of aphids, possibly by alteration of optical cues (Heimbach et al., 2001). Since the early studies of Moericke (1955) and Kring (1964) showed that optically changing the background of plants may contribute to aphid control, several background materials used as a mulch cover have been demonstrated to be appropriate for the control of aphid infestation and aphid vectored viruses in a large number of crop species (Shands and Simpson, 1972; Cartwright et al., 1990; Brown et al., 1996; Liburd et al., 1998; Brust, 2000; Siekmann et al., 2003). Döring et al. (2004b) proposed a mechanism that involves optical camouflage of the plant by straw, as well as rejection flight (Kring, 1972) after landing on the straw mulch. This mechanism is apt to explain the early effects on infestation of potatoes (Table 3) and reduced numbers of aphids landing in the green water traps (Figure 1).

An earlier and higher settling of aphids in unmulched plots compared to mulched ones, can then be seen as the reason for differences later in the season: assuming exponential population growth, early differences in aphid infestation would lead to increasing differences until peak infestation. Accordingly, the effects of straw mulch were clearer at peak infestation than about two weeks after mulch application.

With increasing amount of straw the *additional* effect on aphids decreased (Figure 1). The reason for this is seen in the fact that the percentage of soil covered by straw increases with the amount applied but with decreasing increments, following a saturation curve (Döring et al. 2004a). Therefore, with respect to aphid host finding behaviour increasing the amount of straw beyond 400 g m^{-2} appears to have no further effects. As a consequence, for the application of straw mulch in agricultural practice the economically optimal mulch quantity is probably at or below 400 g m^{-2} (= 4 t ha^{-1}).

It remains to be investigated if the mulch application in potatoes for the control of persistently transmitted viruses is economically justified. Apart from plant protection issues, the effect of straw mulch to protect soil against water erosion and reduction of post-harvest N losses (Döring et al., 2004a) may motivate farmers to adopt this cultural technique.

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5 Response of alate aphids to green targets on coloured backgrounds

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Key words: alighting, behaviour, *Brevicoryne brassicae*, Hemiptera, host finding, mulch, *Myzus persicae*, straw, surface structure, visual orientation

Abstract

To study the effect of background colour on aphid landing on green targets (water pan traps), two field experiments were set up in Hessen, Germany, in 2003. Traps were put onto coloured plastic sheets (13 colours, straw mulch, transparent foil and uncovered soil, Experiment 1). In Experiment 2 green water pans were again put on coloured plastic sheets (red, white, green, yellow), and sheets were sprayed or not sprayed with insect glue. Backgrounds and traps were spectrally characterised with a field radiometer (320 – 950 nm). Aphid catches were highest in traps on uncovered background, and lowest in traps on white or silver backgrounds. For *Brevicoryne brassicae*, *Myzus persicae* (Hemiptera: Aphididae, Macrosiphini) and five further aphid species there was a significant negative correlation between UV-reflectance (320 – 400 nm) and log(N+1)-transformed number of individuals. However, the effect of straw mulch (reduced aphid catches with straw compared to uncovered background), could not be attributed to differences in UV-reflectance, as UV was almost identical in soil and straw. High numbers of alate aphids were caught in traps on dark backgrounds (e.g. black, dark green), which was attributed to the high contrast between background and target. Substantially higher aphid numbers from targets with bare soil than from targets with spectrally similar black backgrounds are thought to be caused by the structure of the background surface: For alate aphids, landing close to the target on smooth surfaces may induce probing and lack of appropriate substrate will result in take-off, whereas soil will not induce probing and aphids will continue to move towards the green targets.

5.1 Introduction

Aphids are important pests of many crops, either acting as virus vectors or directly by feeding on plant assimilates. Of the non-chemical approaches to the control of aphids, the modification of aphid behaviour, especially by preventing flying aphids from alighting on a crop has attracted much interest (Gibson & Rice, 1989). This strategy includes the use of (coloured) mulches for optical repellence of aphids. Several mulch materials have been reported to reduce aphid infestation, number of landing vectors and also virus incidence in several crops. The materials applied included aluminium (Smith et al., 1964; Wolfenbarger & Moore, 1968; Smith & Webb, 1969; Fusco & Thurston, 1970; George & Kring, 1971; Shands & Simpson, 1972; Nawrocka et al., 1975; McLean et al., 1982; Kuroli & Erdélyi, 1990; Jones, 1991), white, black or coloured plastic mulches (Johnson et al., 1967; Brust, 2000), and straw mulch (Jones, 1994; Heimbach & Eggers, 2002; Saucke & Döring, 2004). In addition, living, green mulches have also been shown to reduce aphid infestation (Smith, 1976, Costello, 1995). It has been stated that the repellency of mulches is based on the reflectance properties of the materials (Zitter & Simons, 1980; Simons, 1982; Gibson & Rice, 1989); however, few studies were accompanied with quantitative spectral measurements (Kennedy et al., 1961; Costello, 1995).

Landing alate aphids are known to be attracted by wavelengths around 550 nm (green-yellow to the human eye) (e.g. Moericke, 1950; Moericke, 1951; Hardie, 1989), but there are also species with different preferences (Moericke, 1969). Although repellency of short wavelengths to aphids is well established in general (Kring, 1972), the position of the respective key wavelengths is not clear yet. Furthermore, apart from direct repellency or attractiveness of different colours, also further optical factors of the background such as the optomotor function of the target (Kennedy et al., 1961), or the reduction of the optical contrast between target and background (Moericke, 1955; Müller, 1964) play a role in the host finding process and may explain the observed effects of mulches.

The aim of this study was to contribute to the understanding of the mechanisms of mulch effects, particularly for straw mulch (Saucke & Döring 2004).

5.2 Materials and Methods

5.2.1 Field experimental designs

Two field experiments were carried out on the experimental farm of the University of Kassel at Hebenshausen (Germany, 51°23' N, 9°55' E), 220 – 250 m above sea level, with 7.9°C mean air temperature, 619 mm yearly precipitation, and clay-silt soils on loess. Top soil colour was determined as dark brown (10YR3/3) (Munsell Color, 1975) and the C_{org}-content was 1.0 % (Wildhagen, 1998).

In Experiment 1, green plastic pan traps, 15.5 × 21.0 cm wide and 5.0 cm high, were used for aphid trapping. These were filled with ca. 1 L of tap water and 1 ml of 50 % Tween 20® as an odourless detergent. One trap each was placed in the middle of differently coloured plastic sheets (69.5 × 89.0 cm, Plastoreg Smidt KG, Witzenhausen, Germany). The sheets were pinned to the ground by bamboo sticks (0.5 cm diameter). The colours were (to the human eye) blue, dark blue, bright cyan, green, dark green, yellow, bright yellow, orange, red, white, silver, grey and black. In addition to these 13 treatments, a transparent plastic sheet and a wheat straw layer of the same size were included, as well as a treatment without any cover (i.e. a trap on bare soil). All treatments and the traps were characterised by their spectral measurements (see below). The 16 treatments were set up in a randomised complete block design with four replications; the 64 trapping units (unit = one trap on one background) were separated by bare soil, 1 m in each direction and 3 m between blocks, so that the total experimental area was 6.5 × 35 m. The experiment started on 11 July 2003 and aphids were collected and traps refilled with water and detergent on the 14, 15 and 16 July between 14.00 hours and 16.00 hours (<30 min block^{-1}). The catch was stored in 70 % ethanol until identification following keys of Taylor, (1984) and Heie (1980; 198-1995).

In experiment 2 again, green water traps were placed on coloured plastic sheets (green, yellow, red and white, the same colours as in Expt. 1). As a second factor, the sheets were sprayed or not sprayed with insect glue (Soveurode® Witasek, Austria) in order to investigate which proportion of aphids landing on the sheet would fly or walk into the trap thereafter. The experiment was set up on the 17 July 2003 in a split plot design, with the colour as the main factor, and four replications. Sticky sheets and aphids from traps were collected after 3 h exposure. The weather in the experimental period was hot, dry and mostly cloudless (max. air temp. 22 - 31 °C; mean r. h. 56 - 67 %; no precipitation).

5.2.2 Spectral measurements

Spectral analyses were done with a field radiometer RAMSES-ARC (from TriOs GmbH, Oldenburg, Germany), with a spectral range of 320 – 950 nm in 5 nm steps, a spectral accuracy of 0.3 nm and an opening angle of 7°. As a reflectance standard a 22 × 22 cm Perspex board sprayed with ca. 30 layers of a suspension of 150 : 72 : 1.01 aqua dest : $BaSO_4$: K_2SO_4 was used (Grum & Luckey, 1968; Schutt et al., 1974). The reflectance of this board was measured against an industrial Spectralon™ standard by TriOS. All spectral measurements were done on cloudfree days between 11:00 hours and 13:00 hours to achieve homogeneous insolation conditions, with 0.6 m distance at 90° between radiometer and the objects. The coloured plastic sheets and the green traps (filled with water and detergent) were measured on 2 days with six samples per treatment. Each treatment sample followed a white standard sample (average time difference between treatment sample and standard sample 17 s, maximum 55 s). The treatments 'straw mulch', 'soil' and 'transparent sheet on soil', were sampled within the trapping period (15 July 2003) at four randomly chosen points each (average time difference treatment – standard: 47 s, max. 81 s). The reflectance of all the objects was calculated by dividing the reflectance of the sample by the reflectance of the preceding standard sample, then averaging over all samples per treatment and correcting by the Spectralon™ reflectance. The reflectance curves are presented in Figure 1A to 1D; Figures 1 E and F give an expanded view of the UV region for the same treatments.

5.2.3 Statistical analysis

Statistical tests were done with SAS version 6.12 (SAS Institute Inc., 1989, 1994). All ANOVAs followed GLM procedures. In the ANOVAs aphid numbers were log(N+1)-transformed to stabilise the variances. Back-transformed data are presented. Correlation analysis for aphid numbers (y) vs. spectral reflectance (x) was done by calculation of Pearson´s correlation coefficients for two simple models (log-linear, and log-log). Correlation coefficients were tested for statistical significance with R. A. Fisher´s test (Sachs, 2002).

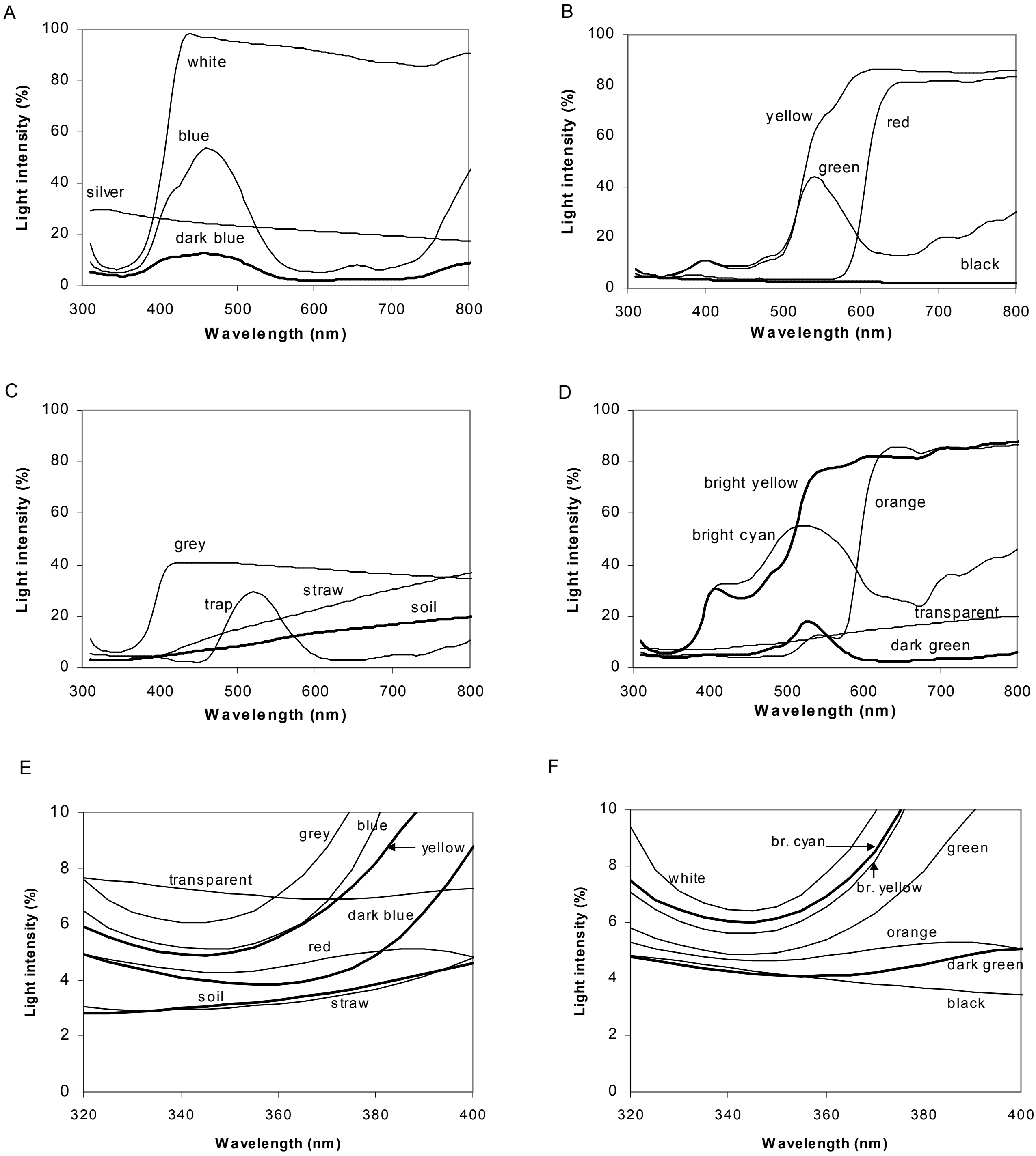

Figure 1. Spectral characterisation of materials used: A - D for the whole spectral range (300-800 nm). Reflectance spectra of (A): white, blue, dark blue and silver background sheets; (B): yellow, red, green and black background sheets; (C): grey background sheet, straw mulch, uncovered soil and green water pan trap with water and detergent; (D): bright yellow, bright cyan, orange, dark green and transparent background sheets. (E) and (F): highlight all treatments in the UV (320-400nm); the silver background is out of scale, compare (A).

5.3 Results

In Experiment 1 the total catch of 55 014 aphids was distributed on 58 taxa, with *Brevicoryne brassicae* (L.) and *Myzus persicae* (Sulzer) being dominant (66.2 % resp. 18.8 %; Table 1). Further taxa with >100 individuals were *Aphis ssp.* (L.), *Metopolophium dirhodum* (Walker), *Capitophorus hippophaes* (Walker), *Acyrthosiphum pisum* (Harris), *Hayhurstia atriplicis* (L.), *Macrosiphoniella tapuskae* (Hottes & Frison), *Hyperomyzus lactucae* (L.), *Capitophorus elaeagni* (del Guercio), and *Rhopalosiphum padi* (L.).

For 10 out of these 11 species, traps on uncovered soil caught the highest aphid numbers, whereas *C. elaeagni* (343 indiv.) revealed the highest catches on dark blue. Traps on white and silver background generally caught the lowest aphid numbers, but this was not consistent for all species (Table 1).

With increasing UV reflectance of the backgrounds (320 – 400 nm) aphid numbers (log(N+1)-transformed) decreased in *B. brassicae, M. persicae*, and *Aphis ssp.* but not in *Metopolophium dirhodum* (Figure 2A to 2E). A significant negative correlation between UV reflectance and aphid numbers was found in seven out of the 11 species with more than 100 individuals (Table 2).

Table 1: Distribution of the five most dominant species in green water traps on differently coloured plastic backgrounds (Experiment 1; mean ± SE). Letters indicate Scheffé grouping of log(N+1)-transformed data.

	All species	*B. brassicae*	*M. persicae*	*Aphis ssp.*	*M. dirhodum*	*C. hippoph.*
N (total catch)	55014	36397	10349	1943	1541	1369
Treatment	Number of indiv.	Average percentage p per trap (n=4)[a]				
Soil	17647 ±1524a	8.1 ±0.9a	8.7 ±0.3a	5.3 ±0.6a	10.4 ±0.6a	6.6 ±1.8a
Red	5821 ±748b	3.4 ±0.5ab	1.1 ±0.1cde	1.9 ±0.3abc	0.3 ±0.1efg	1.2 ±0.1bc
Black	5582 ±1124b	3.4 ±0.8abc	0.6 ±0.1e	2.1 ±0.3abc	0.2 ±0.0fg	0.9 ±0.1bcd
Dark blue	4346 ±466bc	1.8 ±0.3bcd	2.2 ±0.1bc	2.8 ±0.2ab	0.5 ±0.1cdefg	3.0 ±0.3ab
Dark green	3652 ±284bc	1.4 ±0.2bcd	2.6 ±0.2b	2.1 ±0.3abc	1.0 ±0.2bcdef	1.8 ±0.3abc
Straw	2843 ±512bcd	1.3 ±0.3bcd	0.9 ±0.2de	1.9 ±0.3abc	2.1 ±0.5bc	1.2 ±0.2bc
Yellow	2667 ±106bcd	1.3 ±0.1bcd	1.2 ±0.1bc	0.7 ±0.1cde	1.2 ±0.3bcde	1.3 ±0.4bc
Transparent	2589 ±415bcd	1.4 ±0.3bcd	0.7 ±0.1de	1.4 ±0.2bcd	0.3 ±0.0efg	0.5 ±0.2dc
Orange	2088 ±224cde	1.0 ±0.2cde	1.2 ±0.1bcde	0.8 ±0.2cde	0.4 ±0.1defg	0.6 ±0.05bcd
Green	2033 ±334cde	0.8 ±0.2de	1.2 ±0.2bcde	0.8 ±0.1cde	1.4 ±0.3bcd	1.4 ±0.4bc
Br. Yellow	1872 ±261cde	0.3 ±0.0ef	1.7 ±0.3bcd	1.6 ±0.3bc	3.1 ±0.8ba	2.0 ±0.6abc
Grey	1273 ±205ed	0.2 ±0.1fg	1.2 ±0.3cde	0.8 ±0.1cde	1.5 ±0.3bcdef	1.9 ±0.3abc
Blue	887 ±55ef	0.2 ±0.0fg	0.8 ±0.1de	0.9 ±0.2cde	0.8 ±0.1bcdef	1.0 ±0.2bcd
Bright cyan	863 ±18ef	0.1 ±0.0fg	0.7 ±0.0e	0.9 ±0.1bcde	1.1 ±0.4bcde	0.8 ±0.1bcd
Silver	454 ±32f	0.2 ±0.0fg	0.2 ±0.0f	0.4 ±0.1e	0.1 ±0.0g	0.2 ±0.02d
White	397 ±27f	0.1 ±0.0g	0.2 ±0.0f	0.4 ±0.1de	0.7 ±0.1bcdefg	0.4 ±0.1cd

[a] $p = (\Sigma_i(N_{sit}/N_s))/n*100$ where i= replication index with i=1…4, s= species index, t = treatment index. Each column sums up to 25%, i.e. to the average percentage per block.

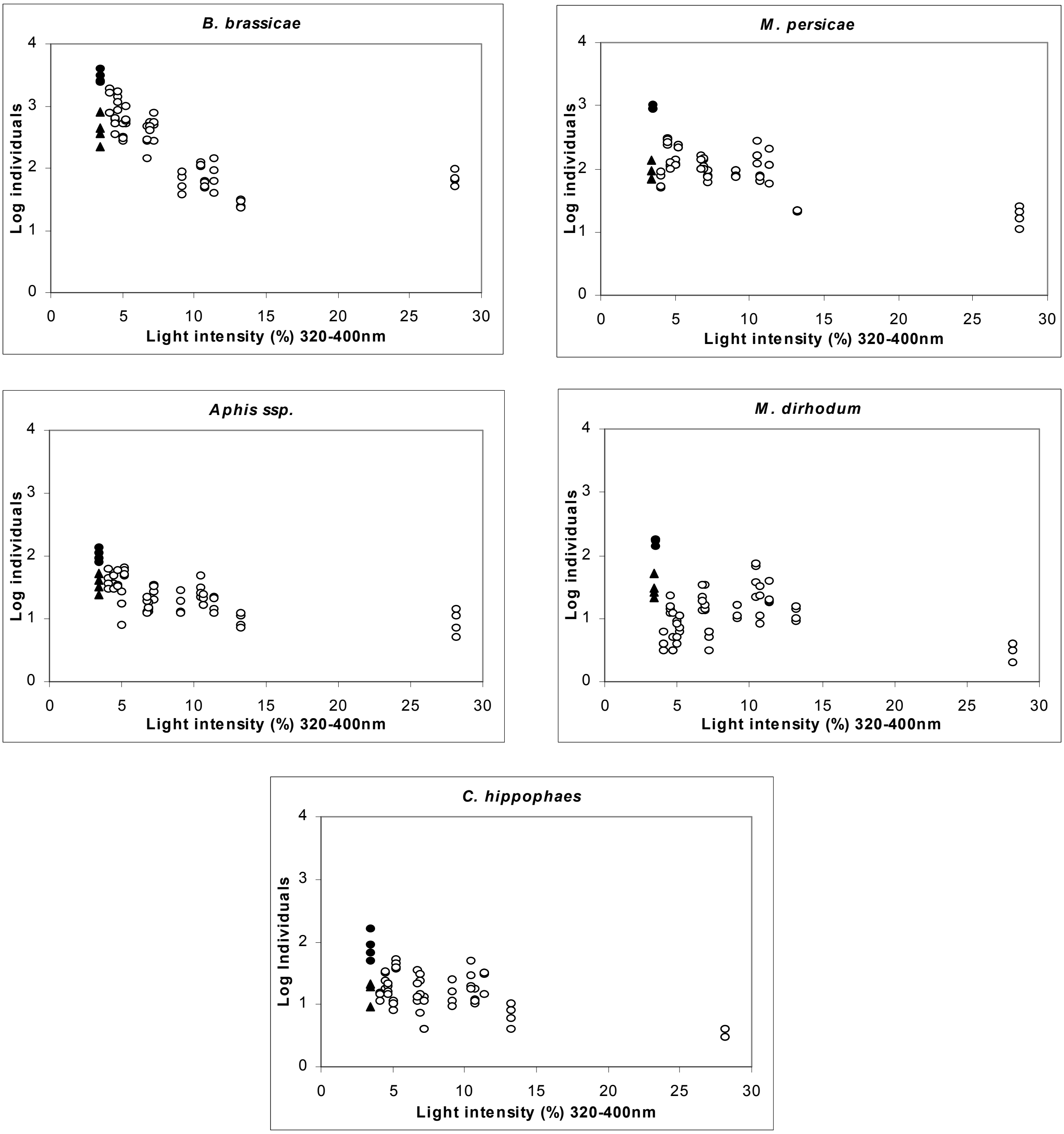

Figure 2. Log(N+1)-transformed numbers of aphids caught in green traps on different backgrounds plotted against the respective mean reflectances in the UV (in %).

▲: trap catches and UV-measurements of the straw background; ●: same for bare soil; ○: all other treatments. (Experiment 1)

Table 2: Correlation between UV reflectance of background sheets and aphid numbers in green traps, Exp. 1.

	r (UV;logN)[a]
B. brassicae	-0.88 ***
M. persicae	-0.53 ***
Aphis ssp.	-0.64 ***
M. dirhodum	0.04 ns
C. hippophaes	-0.33 **
A. pisum	-0.14 ns
H. atriplicis	-0.54 ***
M. tapuskae	-0.34 **
H. lactucae	0.19 ns
C. elaeagni	0.07 ns
R. padi	-0.42 ***
All species	-0.82 ***

[a] Pearson´s correlation coefficient between UV reflectance (= mean light intensity 320 – 400 nm in %) and logN (= log(N+1)-transformed number of aphids per plot); df = 62; * $P<0.05$; ** $P<0.01$; *** $P<0.001$. The silver background as an outlier (Fig. 2A-E) was not included in correlation analysis. Another regression model (potential, i.e. log-log transformation) gave similar results.

Traps on soil caught significantly more aphids than traps on straw mulch in nine of the 11 most dominant species (Table 1; not significant in *A. pisum* and *M. tapuskae*), although these treatments were almost identical in UV reflectance (Fig. 1 E, mean of absolute difference -0.04%, max. abs. diff. 0.24%). Considering individuals from all species, straw mulch significantly reduced aphid catches in traps by 84%.

In Experiment 2, the comparison of aphid numbers in green traps on sticky vs. non-sticky backgrounds revealed very low, non-significant differences (Table 3). Considering only the trapping units with sticky background, landing aphids can either be caught on the background or in the green pan trap. Let N_b denote the number of individuals landed (and caught) on the sticky background; and N_t the number of individuals caught in the pan trap. Then the total catch on the trapping unit is $N_a=N_b+N_t$; and $p_t = N_t/N_a$ is the proportion of landed aphids that directly landed in the pan without touching the background. This proportion p_t (indicating the attractiveness of the trap relative to the background) is plotted against the total catch N_a (representing the attractiveness of the whole trapping unit) in Figure 3. The lowest number of aphids landed on white backgrounds, the maximum catch was on the yellow background. The proportion of aphids that landed in the traps was lowest with green backgrounds, similar with yellow, and highest with red.

Table 3: Aphid catches in green water pan traps on differently coloured backgrounds, which were sprayed or non-sprayed with insect glue (Experiment 2; means ± SE; Letters indicate Scheffé grouping of log(N+1)-transformed data).

Background colour	Individuals in pan on non-sticky background	Individuals in pan on sticky background	Difference
Yellow	15.0 ±1.9a	15.5 ±2.6a	-0.5 ns
Green	8.3 ±2.9ab	7.3 ±1.5a	1.0 ns
Red	9.5 ±3.3ab	10.3 ±2.1a	-0.8 ns
White	2.8 ±1.1b	1.5 ±0.3b	1.3 ns

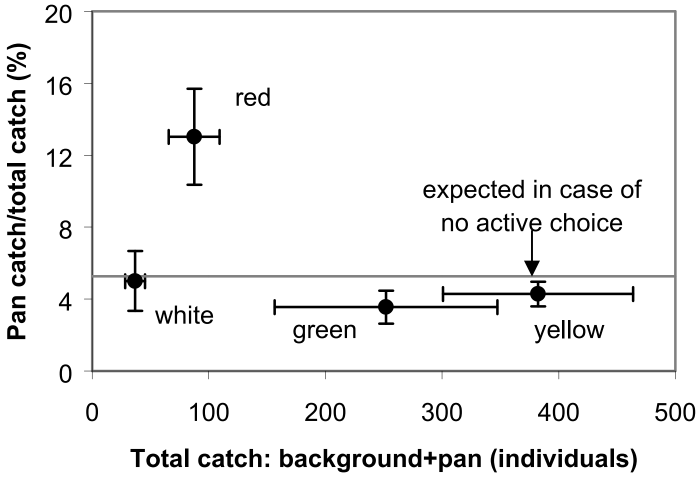

Figure 3. Total number of aphids N_a that were caught on a trapping unit consisting of green traps (aphid catch: N_t) and sticky, differently coloured backgrounds (aphid catch: N_b) ($N_a = N_b + N_t$); and proportion p_t of total catch that landed in traps ($p_t = N_t/N_a$) (mean ± SE). In the case of "no active choice between trap and background" it would have been expected that the proportion p_t equals $R = A_T/A_B$ (with A_T = area of the trap and A_B = area of background sheet); R=5.3%, horizontal line.

5.4 Discussion

With this study, some well known phenomena have been confirmed, such as the repellency of short wavelengths (Figure 2, Table 2; Kring, 1972). The silver background, which was the material with the highest UV reflectance, showed a strong repellency against aphids (Experiment 1). This is in line with many earlier findings, where aluminium – as a material with a known high UV reflectance – was often most effective in repelling compared to other mulch materials or colours (e.g., Jones & Chapman, 1968). For the repellency of the short wavelengths it is still not clear if the UV or the blue region is more important and in this study the effects of UV and blue cannot be separated due to the choice of treatments; however, theoretical considerations (Chittka, 1996; Möller, 2002) and empirical data on colour receptors in insects (Briscoe & Chittka, 2001) have indicated that the short-wave receptor probably lies in the UV region. Differences between aphid species in the response to short wavelength reflection are obvious (Figure 2), but reasons remain unclear, as long as colour receptors are not characterised by physiological studies.

Apart from the short-wave repellency another very well established phenomenon is the strong attractiveness of a green-yellow colour (around 550 nm) to aphids (Moericke, 1955; Kieckhefer et al., 1976; Pelletier, 1990) and this was confirmed in Experiment 2 (Figure 3, x-axis). Despite this attractiveness, yellow and green as background materials decreased aphid catches compared to uncovered soil (Table 1), although soil shows a low reflectance in the 550 nm region (Figure 1C). This apparent contradiction between the general attractiveness of yellow or green and the comparatively low catches in traps on yellow resp. green backgrounds has been explained with a low contrast or colour difference between target and background (Moericke, 1955; Müller, 1964). Consequently, despite being attracted by a yellow or green background in Experiment 2, only a low proportion of all aphids caught on a trapping unit landed in the traps (Figure 3).

This "contrast" explanation also predicts that a black background, showing a higher contrast to the green target than soil, would lead to higher numbers of aphids caught in traps than in the unmulched soil treatment. Our results, however, indicate that black mulching decreases aphid numbers compared to uncovered soil, and this is backed by earlier findings (Johnson et al., 1967; Jones & Chapman 1968; Brust 2000). For the explanation of this phenomenon we suggest that the spectral traits of soil and mulch as well as post-landing behaviour need to be considered.

Aphid landing can either take place on the background or on the target, and observations indicate that aphids do not always land directly on the target but land also on non-attractive backgrounds near to the target, even on soil (Moericke, 1955). Once it has landed on the background, an aphid will either consider the surface as a leaf or as a non-leaf. We suggest that this decision will not only depend on the colour (Moericke, 1950) but also on the surface structure and tactile cues (Moericke, 1950): Smooth surfaces (such as leaves, straw, or plastic sheets) will be considered as leaves and induce probing activity, whereas soil may be easily distinguished from leaves by its rough surface and no probing is done. After probing in vain on smooth surfaces (like plastic, straw or a non-host leaf), the aphid will take off again (Kennedy 1966; Kring, 1972, p. 471, 'rejection flight') and will not fly or walk towards a target like the trap in our experiments. This is supported by the low, non-significant differences in aphid catches from traps on sticky and non-sticky backgrounds (Table 3). However, after landing on soil, where most probably no probing is done, the aphid will keep on moving (by flight or walking) towards the green target. This could explain why traps on uncovered soil as background mostly catch more aphids than traps even on black (smooth) background (Table 1); this effect was already observed by Moericke (1955) and termed 'Erdfaktor' (soil factor).

Straw mulch lead to reduced aphid numbers in green traps compared to unmulched soil (Experiment 1), confirming results obtained in potatoes (Saucke and Döring 2004; Heimbach et al., 2002), lupins

(Jones, 1994), faba beans (Heimbach et al., 2002), and rape (Heimbach et al., 2001). Due to the very low differences in ultraviolet reflectance between soil and straw this effect (Figures 1E and 2) cannot be attributed to UV repellency. Therefore, the lower contrast between trap and background with straw than with soil (measured as the light intensity difference between background and trap in the yellow-green band, compare Fig. 1 C) is probably involved in the reduction of aphid numbers. Presumably, the rejection flight after probing on straw also plays a role; preliminary observations in laboratory choice experiments with the potato aphid *Aulacorthum solani* (Kaltenbach, 1843) indicate that straw is indeed optically attractive to alate aphids, as they regularly approached a straw sample on soil background, probed on it, and left it after some probing (T.F. Döring, S.M. Kirchner, unpubl.).

Summarising, three supposed mechanisms are involved in the effects of mulches on aphid landing: First, backgrounds with a high reflectance in the short-wave region directly repel alate aphids (e.g. white, aluminium). Second, a low contrast between background and green target decreases the probability of landing on the green target (e.g. green, straw). Third, the background acts as an optical competitor to the green target and a non-host contact on this background induces the insect to leave the patch where it had landed (e.g. green, straw); this last mechanism is similar to the appropriate/inappropriate landing theory presented by Finch & Collier (2000).

Apart from diffuse reflectance, direct reflectance (mirroring or glittering appearance) might also play a role in aphid repellency of mulches, however, there are no investigations known to the authors to substantiate this supposition.

For the choice of mulch material and colour from the variety of available mulches for application and optimisation, it is of course not sufficient to consider only the effects of optical factors on insect pests. However, for a comprehensive applied view, other associated agronomic effects must be regarded too, such as the effects on yield (Singh et al., 1988; Brown et al., 1991; Brown et al., 1996), crop quality (Antonius, 1996), the effects on soil erosion (Edwards et al., 2000) and nitrogen dynamics (Cheshire et al., 1999) or the degradability and prize of the material. Regarding these parameters, straw mulch based approaches appear to have a high potential for adoption in practice.

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

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 to 5 t ha^{-1}, on soil nitrate dynamics, weed development, tuber yield and soil erosion, twelve field experiments were evaluated. Experiments were conducted on organic farms over three years at two locations in a temperate climate (635 to 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 immobilisation of nitrate-N after harvest at 6.8-7.0 kg N t^{-1} straw in two experiments (18 to 34 kg NO_3–N ha^{-1}). 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^{-2}) in the unmulched treatment, and 31, 42 and 26 g m^{-2} in treatments with chopped straw at 1.25, 2.5 and 5 t ha^{-1}, respectively.

Keywords: Straw mulch, Nitrogen, Organic farming, Potato, Soil erosion, Weeds

6.1 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 lead 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 North America (Albrecht, 1922; Rowe-Dutton, 1957), and it was recognised that straw mulch might be useful against "degeneration", i.e. for virus control in seed potatoes (Werner, 1929; also see Emerson, 1907); but straw mulching in potatoes disappeared from commercial practice when its function to increase soil moisture (Russel, 1940; Verma and Kohnke, 1951) was taken over by sprinkler irrigation (Pavlista, 2004, University of Nebraska, pers. comm.), and weed suppression (Rowe-Dutton, 1957) was achieved by the use of herbicides. With this shift, however, associated beneficial effects of straw mulch were also lost, one of the most important being the reduction of soil erosion (Duley and Kelly, 1939; Borst and Woodburn, 1942a; Dawson, 1946; Adams, 1966; Edwards et al., 2000).

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

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

To make use of these benefits under temperate climatic conditions, where soil moisture in summer is rarely limiting potato growth, it therefore appears to be reasonable to apply only small to moderate amounts of straw, thereby avoiding the risk of reduced yields in cool and wet growing seasons. In order to evaluate this approach the yield response to mulching with straw applied at 2.5 to 5 t ha^{-1} was quantified in eleven field experiments that were conducted over three years at two locations in Germany. An additional field experiment was set up on-farm in order to quantify effects of small to moderate amounts of straw mulch on soil erosion under conditions of organic potato growing.

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

6.2 Material and Methods

6.2.1 Field experimental design

Spreading straw on potato fields shortly after crop emergence (mulching) was compared to non-mulching (bare soil) in eleven field experiments. The experiments were conducted on two organically managed farms in Germany: (A) The experimental farm of the University of Kassel at Hebenshausen and Neu-Eichenberg, (51°23' N, 9°55' E) ca. 16 km S of Göttingen, 220 to 250 m above sea level with clay-silt soils on loess (13–15 % clay, 78–83 % silt, 3–6 % sand); and (B) an arable farm ca. 17 km ESE of Göttingen (51°28' N, 10°08' E) ca. 240 to 280 m above sea level with loamy soils (20–24 % clay, 73–76 % silt, 3–6 % sand). Climatic conditions of the experimental years and locations are summarised in Table 1.

Table 1: Air temperature (°C) and precipitation (mm), from April to August in 2001-2003, and the long term average at two experimental sites. Data from weather station of the University of Kassel agricultural experimental station (site A) and from a Deutscher Wetterdienst (DWD) station (site B).

	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.[b]	19.3	
	1977-2000	45.2	53.9	75.7	62.7	54.4	635.2
Precipitation site B[a]	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

[a] 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

[b] s.d. sampler defect, but own observations indicate that precipitation was below long time average, around 15 mm.

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

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

[a]: varied plot size: 10 x 10, 20 x 20 and 30 x 30 m; plot size had no significant effect on yield.

[b]: experiment type; "on-farm" experiments were marked within farmers´ fields, "extra" (small scale) experiments were surrounded by 3 m wide strips of bare soil

[c]: earlier date in presprouted, later date in non-presprouted potatoes. No significant interaction between mulch and presprouting regarding yield.

[d]: varied amounts: 1.25, 2.5 and 5.0 t/ha.

[e]: harvest of mature tubers occurred blockwise on two dates; haulms had already died back completely before harvest.

[f]: green manure over winter after winter cereals.

For all experiments mulched and non-mulched plots were either marked within existing potato fields or were set up as separate small-scale experiments (Table 2). Dates for planting, mulching and harvest, as well as mulch quantities and plot sizes are presented in Table 2. In all years weeds were controlled twice before mulch application with a rotary finger wheel hoe with ridging discs (site A) or a Wühlmaus Ridging Hiller (site B). Haulm death was caused by late blight (*Phytophthora infestans* Mont. de Bary) in 2001 and 2002, and was cut in 2003 after plant growth had stopped due to hot and dry weather. Chopped straw mulch was applied by hand in exp. 1, 4 and 5; with a Kverneland Round bale chopper (KD 807) in exp. 2, 6 and 7; and with a Hawe Stable Straw Spreader in exp. 8 to 12. All experiments were conducted in randomised complete block designs with four replicates. Further details of experiments 1, 2, 4 and 5 are presented in Saucke and Döring (2004). In exp. 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.

6.2.2 Soil sampling

Soil was sampled at two depths (0–30 cm and 30–60 cm) in exp. 1, 4 and 11 with a Göttinger soil sampling set (diameter 18 mm). Bulk samples of each plot were obtained from eight (exp. 1) or ten (exp. 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 exp. 1 was done shortly before harvest (23 July 2001); sampling in exp. 4 and 11 was done at three dates per year (1) at plant emergence (22 Apr. 2002, 22 Apr. 2003), (2) after haulm death shortly before harvest (6 Aug. 2002, 22 July 2003) and (3) three to six weeks after harvest and before emergence of the following green manure crop (24 Sept. 2002, 10 Sept. 2003). Samples were cooled in the field and frozen at –18 °C until moisture content was measured (weight loss after 24 hrs at 105 °C; exp. 1, 4 and 11) and analysis of mineral N was done for samples of exp. 4 and 11 with 100 g soil and $CaCl_2$-extraction (VDLUFA, 1991; König and Fortmann, 1996).

6.2.3 Plant growth parameters

In exp. 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 Ldt, 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 exp. 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 summarised in Table 5.

6.2.4 Weed assessments

Weed development was investigated in five experiments. In exp. 1, 9 and 12, a sampling frame of 0.40 m x 1.60 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 exp. 7 and 8 the above ground biomass of weeds was cut from four randomly chosen sampling areas per plot, measuring 1.50 m x 1.50 m each. The weeds were dried at 80 °C until constant weight.

6.2.5 Harvest and yield measurement

Harvesting was done with a "Samro Spezial" potato lifter with cleaning drum in exp. 1, 4 and 5 and by hand in all other experiments. Per plot, seven subsamples were taken in exp. 1, 4, and 5; two in exp. 2; nine in exp. 6 and 11, five in exp. 7 to 10; and sixteen in exp. 12; row length per subsample was 9 m in exp. 1, 4, and 5; 3.5 m in exp. 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 mm, 35–65 mm and >65 mm in exp. 1 and 2; and <35 mm, 35–55 mm and >55 mm in all other experiments).

6.2.6 Soil erosion

Soil erosion was measured in an unreplicated artificial rain experiment (exp. 3; at 20 % crop cover and with a slope of 8 %), using a mobile rainfall simulator developed by Kainz and Eicher (1990) (Auerswald and Eicher, 1992; Auerswald et al., 1992; Kainz et al., 1992), with 4 horizontally oscillating Veejet 80100 nozzles (Moore et al., 1983). The maximum rain drop size is 10-20 mm diameter and 13 % of drops are below 3 mm (Hassel and Richter, 1992). Nozzle height (2.8 m) and water pressure (42.2 kPa) resulted in an adjusted dropping height of 3.5 m. The rain interval was 60 min per plot, the first 20 min with artificial rain intensity of 60 mm h^{-1}, the last 40 min with 80 mm h^{-1}. The sum of applied rain within 1 hour of simulation was 73 mm. The kinetic energy of the first 20 min was 382 J m^{-2}, of the last 40 min 1012 J m^{-2} (Hassel and Richter, 1992). Treatments were mulch of chopped winter wheat straw (mean length 58 mm; SD 41 mm) at 1.25 t ha^{-1}, 2.5 t ha^{-1} and 5.0 t ha^{-1} and uncut (long) straw at 2.5 t ha^{-1}, as well as an unmulched control. Runoff delay after starting the artificial rainfall was determined and runoff was continuously measured and collected.

Sediment concentration (g l^{-1}) was determined by drying runoff at 105°C (Brandt, 1997). Afterflow was measured as the time between end of artificial rainfall and end of runoff.

6.2.7 Estimation of area covered by varied amounts of straw

In order to establish the relationship between the quantity of straw applied and the percentage of the area covered by straw mulch, wheat straw (dry matter content 94.0 ± 0.1 %) was distributed on the object table (48.5 cm x 31.5 cm) of a leaf area meter (Delta-T Devices Ltd, Cambridge, UK; Monitor Hitachi VM900, Interface RS 232c; Video-Camera TC 1005/01X, RCA, Lancaster). The amount of straw on the object table was gradually increased in 5 g steps from 0 to 50 g. Three treatments were measured with three replicates each: (i) straw cut into regular, 50 mm long pieces (ca. 5 mm wide; double-sided internodes only); (ii) chopped straw, piece length <35 mm (measured from n = 344 pieces ≥ 10 mm); and (iii) unchopped straw, average piece length 75 mm (measured from 50 g, n = 833 pieces; SD = 58 mm; 25 % of pieces >100 mm). To achieve a random distribution of the straw on the object table, the straw was dropped from a height of 2.32 m through a cardboard tunnel (ground area: 34 cm x 26 cm) placed vertically on the object table; the tunnel was carefully removed from the object table before each area measurement.

6.2.8 Statistical analysis

Statistical analysis was performed with SAS v6.12 (SAS Institute Inc., 1989; SAS Institute Inc., 1990). Percentage values, such as tuber size fractions, weed cover estimates and soil moisture contents, were arcsin-square-root transformed before ANOVA. Untransformed data are presented.

6.3 Results and Discussion

6.3.1 Soil moisture

Soil moisture measured directly before harvest in three expts. was not affected significantly by mulching (Table 3).

Table 3: Effect of straw mulch in potatoes on soil moisture shortly before harvest (weight–%): means ± SE.

	Exp. 1 (2001, n = 8)		Exp. 4 (2002, n = 4)		Exp. 11 (2003, n = 4)	
Soil moisture pre-harvest	0-30cm	30-60cm	0-30cm	30-60cm	0-30cm	30-60cm
Unmulched	17.7 ±0.5	19.0 ±1.1	21.1 ±2.8	20.2 ±2.3	8.8 ±0.3	11.7 ±0.2
Mulched	18.9 ±0.8	18.0 ±0.6	21.1 ±2.3	20.6 ±3.1	9.3 ±0.3	11.8 ±0.2
LSD 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)

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

It is known that the moisture conserving effect of straw mulch increases with the amount applied (Russel, 1940). Verma and Kohnke, (1951, p. 150) stated that an amount of 3,000 pounds of mulch per acre [=3.4 t ha^{-1}] is about the smallest rate that is effective in evaporation control. Therefore, the relatively small amounts of straw applied would not be expected to be effective in conserving soil moisture.

6.3.2 Soil nitrate dynamics

At emergence and immediately before harvest, only small and non-significant differences in soil nitrate between mulched and unmulched plots were found (Table 4). Nitrogen mineralisation after the harvest process lead to a post-harvest increase of nitrate in the soil (62 and 51 kg NO_3-N ha^{-1} in the unmulched soil, exp. 4 and 11, resp.). The post-harvest amount of nitrate was greater in the unmulched than in the mulched plots with a total difference of 33.8 kg NO_3-N ha^{-1} in exp. 4 (not significant) and 17.6 kg NO_3-N ha^{-1} in exp. 11 (significant at p= 0.035; Table 4).

The reason for this is seen in an immobilisation of nitrogen after incorporation of the (partially decayed) 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 exp. 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 ton straw applied, ca. 6.8 and 7.0 kg N (exp. 4 and exp. 11, resp.) were immobilised; this immobilisation rate is at the upper end of the range (1 to 7 kg N t^{-1}) summarised by Christensen and Olesen (1998).

Table 4: Effect of straw mulch applied to potatoes (var. Christa) on soil nitrate-N (kg ha^{-1}) in two experiments[a]: means ± SE, n = 4.

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

[a]: for details of experimental conditions see Table 2; for sampling dates see section 6.2.2.

[b]: There were no significant differences between mulched and unmulched treatments concerning soil nitrate at emergence and pre-harvest.

ns: not significant; *: $p<0.05$

6.3.3 Parameters of plant nutritional status and plant growth

Hydro N-Tester values, as a measure of the nutritional status of the plant, were significantly reduced by straw mulch application in exp. 1 (Fig. 1). Effects on plant height were small, not exceeding 2.2 cm, although these effects were significant in two cases on Nicola, but not on Marabel and Christa. Also, effects were only significant when either the number of plants per plot or the number of replications was unusually high (Table 5).

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.

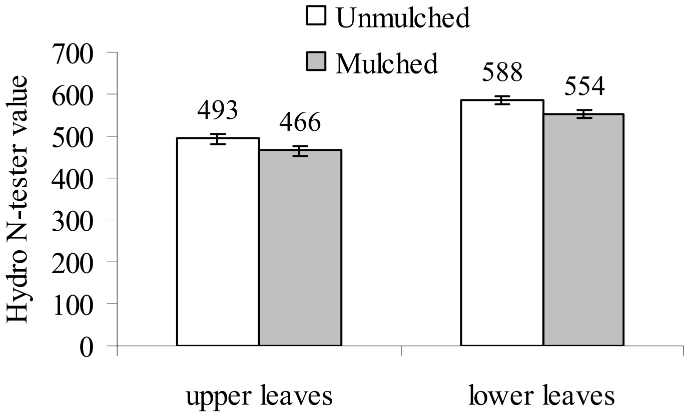

Fig 1: Hydro N-Tester value as affected by straw mulching (exp. 1). Means ± SE; n = 8. Mulching effect significant at p < 0.001; effect of leaf position significant at p < 0.001. Interaction between mulching and leaf position not significant.

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
LSD 5 %	1.5 *	3.8 ns	2.6 ns	2.8 ns	1.57 *

ns: not significant; *: p<0.05

6.3.4 Weeds

The most dominant weed species were *Fumaria officinalis* in exp. 1, *Polygonum persicaria* and *Cirsium arvense* in exp. 7 and 8, *Thlaspi arvense* and *Chenopodium album* in exp. 9, and *Stellaria media* and *Chenopodium album* in exp. 12. There were no consistent effects of mulching on the number of weeds, weed cover and biomass (Table 6, Figure 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 exp. 1: Earlier in the season (6 June) mulching increased the number and cover of weeds, while three weeks later (27 June) the number of weeds was reduced; this reduction was significant overall (i.e. for both sampling positions together) and for the lower sampling position ("in furrows"), but not for the top half of the ridge profile. While weed reduction by light-excluding mulches has been reported widely

(Rowe-Dutton, 1957; Prihar et al., 1976), a possible compensatory effect occurs when weeds benefit from increased soil moisture under light mulches (Jacks, 1955; Jalota and Prihar, 1979), and this may explain the increased number of weeds early in the season in exp. 1. After several weeks, the straw mulch had partly slid off the top half of the ridge and accumulated on the bottom where it impeded weed growth. Indirect detrimental effects of mulch on yield through the promotion of weeds have been reported (Zhivan 1935, cited in Jacks 1955), but here, for a negative effect of weeds on yield, overall weed cover was too little.

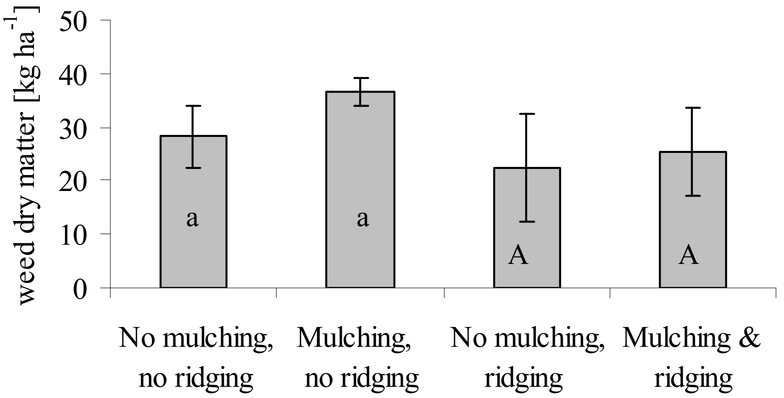

Fig. 2: Weed dry matter (kg ha^{-1}) on 9 July 2002, as affected by mulching in exp. 7 (ridged after mulching, upper case letters) and exp. 8 (not ridged after mulching, lower case letters). Means ± SE; n = 4. Means with the same letter within the same case (i.e. within the same experiment) are not statistically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

Table 6: Effect of straw mulch and sampling position on weed counts (number of plants per m²) and weed cover (%) in experiment 1, 9 and 12.

Parameter	count/m²				cover (%)				
Experiment	1	1	9	12	1	1	9	12	12
Date	06.06.	27.06.	12.06.	18.06.	06.06.	27.06.	12.06.	18.06.	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	-[a]
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 df	21	21	9	9	21	21	9	9	7
number of subsamples	2	2	2	8	2	2	2	8	10

[a]: not sampled * 0.01< p <0.05; ** 0.001< p <0.01; *** p <0.001; ns not significant.

The main reason why weed growth was not influenced consistently by straw mulch in the experiments presented is again seen in the comparatively small application rates. Bushnell and Welton (1931) found that at application levels below 8t/acre [= 19.75 t ha^{-1}], annual weeds readily penetrated the mulch. Similarly, Hembry and Davies (1994) found weed growth still occurring at 20 t ha^{-1} of straw mulch, although with few weeds.

6.3.5 Yield and tuber size fractions

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

Table 7: Effect of straw mulching on tuber yield of potatoes. Means ± SE.

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

[a] Experiment 7: Straw was partly incorporated into soil with finger wheel hoe 6 weeks after mulching

[b] Experiment 10: Straw was partly incorporated into soil due to strong rainfall (ca. 50 mm in 2 hours) already 3 days after mulching

[c] Total yield of Exp. 1-5: Figures have already been presented in Saucke & Döring (2004)

[d] Small fraction <35 mm; large fraction > 65 mm in exp. 1 & 2 and >55 mm in exp. 4 - 11.

ns: difference not significant; * $p<0.05$

These results are in agreement with recent investigations on straw mulch effects from temperate climates, which also did not show any significant yield response of potatoes to straw mulch (Stoner et al., 1996; Edwards et al., 2000, data not presented). As pointed out by Jacks (1955), mulching affects crop yields in many and complex ways. Higher yields under mulch have mostly been attributed to increased soil moisture under arid and semiarid conditions (Singh et al., 1987; Singh et al., 1988; Saha et al., 1997; Tiwari et al., 1998; Tolk et al., 1999; Ramalan and Nwokeocha, 2000; Chandra et al., 2002) but even in the comparatively hot dry summer of 2003 (see Table 1) yields were not significantly affected by straw mulching. Reasons for the tuber yield not being affected by straw mulch may include the compensation ability of the plant under water stress conditions, the high water holding capacity of the soils and the comparatively low evaporativity during the experimental periods; however, the main reason is seen in the low amount of straw applied, as already soil moisture was not influenced significantly by mulching (see above).

6.3.6 Soil erosion

Soil loss was greatest in the unmulched plot with 1606 g m^{-2} (Table 8); similar values were found by Lal (1975) with 1219 and 2706 g m^{-2} on 5 % and 10 % sloping unmulched soil, respectively. Even very small amounts of straw mulch (1.25 t ha^{-1}) decreased soil loss and sediment concentration in runoff. While cut straw reduced soil loss by 97.4–98.4 % compared with untreated soil, reduction of soil loss by long straw (2.5 t ha^{-1}) was less effective (reduction by 91.7 %). Similar results were found in other investigations. With straw application levels of 2 and 4 t ha^{-1} at 10 % slope, Lal (1975) found soil loss reduced by 97 % and 99.6 %, resp., compared to soil loss in unmulched treatments. On a 12.5 % sloping silt loam, an application of ca. 5 t ha^{-1} lead to a reduction in soil loss by 98.0–99.9 % (Borst and Woodburn 1942b).

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^{-1}] 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^{-1}]	69.0	3.4	2.2	1.1	10.5
Max sediment concentration [g l^{-1}]	101.7	5.1	8.0	1.9	41.4
Soil loss per plot [g]	10357	199	270	170	857
Soil loss [g m^{-2}]	1606	31	42	26	133
Soil loss [%]	100	1.9	2.6	1.6	8.3

During rain simulation the straw was partly washed from ridges into furrows and formed micro-dams, building a lined-up microrelief which retained the surface rainwater in small hollows as was already observed by others (Roth and Helmig, 1992; Brandt 1997; Roth, 1998). As a result, afterflow was increasingly delayed with increasing straw quantity from 2.7 min in untreated to 39.7 min in 5 t ha^{-1} straw mulch. Long straw also formed dams and built up hollows, but the effect of runoff filtration was less marked than in the treatments with chopped straw. Due to the application of straw mulch onto ridges and their transportation into furrows by the rain, the effect of reduced soil crusting on the upper half of the ridge was small. Soil crusting, as a result of the artificial rain, lead to considerable runoff. The main effect of straw mulch is seen in the sediment retention (Brandt and Wildhagen, 1998). Therefore, only small amounts of straw are necessary for avoiding soil erosion in ridge till systems like potato cultivation.

6.3.7 Coverage by straw mulch as affected by the amount applied

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

The comparison of the figures from the leaf area meter to a (ridged) soil should be considered with caution. First, the soil surface usually is considerably rougher in contrast to the smooth object table used; this will probably increase the amount of straw needed to cover a given soil area. Second, in the field the straw (with a typical range of 80 to 90% dry matter) is not as dry as the material used here. Despite these restrictions, the data are in very good accordance with those presented by Borst & Woodburn (1942b), who estimated that 1 ton/acre of long straw (=2.47 t ha^{-1}) covered 75–85 % of an unridged soil, although figures for straw dry weight were not given.

Finally, it should be considered that by ridging, the area to be covered approximately increases by a factor of $f = (x^2+y^2)^{0.5}/y$ where x = height of ridge from bottom to top and y = distance between rows. At x = 30 cm ridge height and y = 75 cm row spacing, this factor is f = 1.077, e.g. 3.0 t ha^{-1} for flat surfaces would have to be adjusted to 3.23 t ha^{-1} on ridged surfaces. The results presented here indicate that 5 t ha^{-1} of chopped straw covers >95 % of the ridged soil.

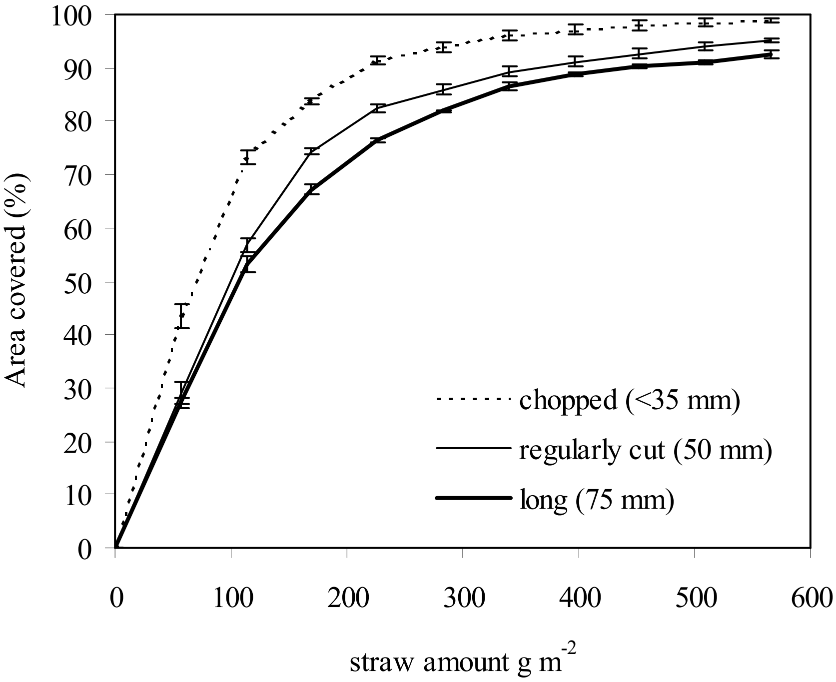

Fig. 3: Area covered by varied amounts of wheat straw of different size classes, measured by leaf area meter; means ± SE, n = 3.

6.4 Conclusion

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

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

Finally, in this study, moderate amounts of straw neither reduced nor enhanced weeds significantly. A prerequisite for compatibility of straw mulch application and mechanical weed control was, however, that a sufficient weed control was possible before straw application. This kept overall weed levels moderate during the whole vegetation period in all experiments. If weeding is done after mulching, i.e. when the straw is incorporated during the growing period, there will be the risk of N immobilisation and the straw cover will at least partly be destroyed and optically mediated effects on virus vectors will be lost. On the other hand, the benefits of moving and aerating the soil by mechanical weeding, principally N mineralisation, could economically overcompensate these effects. Due to the possibly conflicting objectives of good straw mulch coverage on the one hand, and the need for mechanical weed control measures in organic potato growing on the other hand, weed control in organic straw mulch systems requires further attention.

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

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7 Effect of straw mulch on late blight (*Phytophthora infestans*) and black scurf (*Rhizoctonia solani*) in organic potatoes

Abstract

The application of straw mulch is a strategy for soil erosion control, virus control and reduction of post-harvest soil nitrate losses. The effects of mulching on severity of late blight (*Phytophthora infestans* (Mont.) de Bary) and black scurf (*Rhizoctonia solani* Kühn) were assessed in nine organically managed field experiments over three years. Late blight severity was estimated in five of the experiments at 3 to 7 dates per experiment. Black scurf on harvested tubers was assessed with 100 to 220 tubers per plot. In addition, effects of straw mulch on air temperature and relative humidity in the potato stand was measured in one experiment. Straw mulch had no significant effect on late blight severity, measured as relative area under the disease progress curve, in any of the experiments, but a trend reducing late blight through the application of straw mulch was observed in all five experiments. Black scurf was not influenced consistently by straw mulch, with effects being non-significant in eight out of nine experiments. Effects of straw mulch on microclimate within the crop canopy were dependent on the time of the day, with the air in mulched plots being moister and cooler at night and dryer and warmer during the day. This effect was pronounced in the fortnight directly after mulching and became less in the period four to six weeks thereafter.

7.1 Introduction

The application of straw mulches to various agricultural crops is an ancient practice (King, 1984), serving a variety of aims, such as moisture conservation (Russel, 1940; James, 1945; Mooers et al., 1948; Jalota and Prihar, 1979), weed suppression (Hembry and Davies, 1994), or improvement of soil organic matter status (Jacks et al., 1955). In potatoes, straw application was practised in the early 20th century in North America (Knowlton et al., 1938; Rowe-Dutton, 1957), but disappeared from commercial growing and is now only used to some extent in home gardening. However, experimental evidence suggests that straw mulch could improve environmentally and economically important aspects of commercial potato growing, as straw mulch was repeatedly shown to massively reduce soil erosion (Borst and Woodburn, 1942a; Adams, 1966; Edwards et al., 2000; Döring et al. 2004). Moreover, benefits of straw mulch regarding virus vector control in seed potatoes have been reported (Emerson, 1907; Heimbach et al., 2000; Heimbach et al., 2002; Saucke and Döring, 2004). Finally, straw mulch may also act as a tool for control of nitrogen losses by immobilisation of post-harvest soil nitrate (Christensen and Olesen, 1998; Cheshire et al., 1999; Döring et al., 2004).

In order to assess the prospect for the re-adoption of this cultural technique, however, it is necessary to investigate possible side effects of straw mulch on plant health and tuber quality. Two of the most important diseases in current organic potato growing are late blight and black scurf (Möller et al., 2003). Late blight, caused by *Phytophthora infestans* (Mont.) de Bary, is commonly considered to be one of the most important yield limiting factors in organic potato production. Also, *Rhizoctonia solani* (Kühn) is a severe problem in organic potato growing, because infestation with black scurf, i.e. sclerotia on the tubers that cannot be removed by washing, reduces marketability of ware potatoes. Moreover, sclerotia on seed potatoes serve as inoculum in the field potentially reducing the emergence of the crop considerably (*e.g.*, Powelson et al., 1993). This is the first study known to the authors dealing with the response of these two diseases to straw applied as a mulch after crop emergence in potatoes.

7.2 Material and methods

7.2.1 Field experimental design

Nine field experiments were conducted on two organically managed farms in Germany over three years: (A) The experimental farm of the University of Kassel; (B) an arable farm near Göttingen. Geographic co-ordinates, climatic conditions and soil texture of the locations are summarised in Table 1. Dates for planting, mulching and harvest, as well as plot sizes and pre-crops are presented in Table 2. In all years weed control was done two times before mulch application with a rotary finger wheel hoe with ridging discs (site A) or a Wühlmaus Ridging Hiller (site B). Further details of experiments 1 to 8 are presented in Saucke & Döring (2004) and Döring *et al.* (2004). All experiments were conducted in randomised complete block designs with 3-16 replications (Table 4). In order to minimise interplot interaction with respect to virus spread, the plots were arranged in a line approximately across the main wind direction (Thresh 1976; Saucke & Döring 2004). Row direction was parallel to this line.

Table 1: Details of experiments: location of study sites

Site	A	B
Name of location	Eichenberg	Etzenborn
Nearby city	Kassel	Göttingen
Latitude	51°23' N	51°28' N
Longitude	9°55' E	10°08' E
Altitude (m)	220 - 250	240 - 280
Mean air temp.(°C) (1977-2000)	8.1	8.1
Precip. (mm/year) (1977-2000)	635	709
soil texture	silty loam	sandy loam

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

Exp.	Year	Site	Variety	Plot size (m x m)	Planting date	Mulching date	Mulch (t/ha)[b]	Date of harvest	m harvested per plot	Precrop[d]	Numbering in Döring et al. 2004
1	2002	A	Christa	9 x 9	10.4.	16.+26.5.[a]	5.0	14.+16.8.[c]	63	grass-clover	4
2	2002	A	Nicola	9 x 9	15.+20.5.	3.+10.6.[a]	4.0	23.+24.9.[c]	63	grass-clover	5
3	2002	B	Christa	9 x 30	5.4.	17.5.	3.5	5.8.	27	carrots	6
4	2002	B	Nicola	15 x 25	8.4.	17.5.	3.5	28.8.	15	winter wheat	7
5	2002	B	Nicola	3 x 25	8.4.	17.5.	3.5	28.8.	15	winter wheat	8
6	2003	A	Marabel	24 x 18	17.4.	28.5.	3.0	3.9.	15	summer wheat	9
7	2003	A	Rosella	18 x 30	17.4.	28.5.	3.0	4.9.	15	cabbage	10
8	2003	B	Nicola	30 x 27.5	15.4.	21.5.	3.0	26.8.	48	peas	12
9	2004	B	Christa	9 x 30	31.3.	18.5.	5.0	-	-	grass-clover	-

[a]: earlier date in presprouted, later date in non-presprouted potatoes. No significant interaction between mulch and presprouting regarding *Phytophthora* or *Rhizoctonia*.

[b]: ±0.25t/ha

[c]: harvest of mature tubers occurred blockwise on two dates; haulms had already died back completely before harvest.

[d]: green manure over winter after winter cereals.

In exp. 1, 2 and 8, 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.

7.2.2 Microclimatic measurements

The development of late blight is strongly dependent on high humidity (Stevenson, 2001). Therefore, the influence of straw mulch on microclimate, including relative humidity was investigated. Microclimatic measurements were done with Hobo data loggers (Onset Ltd.) in experiment 1 (2002, site A). The device was protected from direct insolation by an aluminium roof (ca. 18 x 17 cm). In four mulched and four unmulched plots (paired by blocking), one logger per plot was placed on top of the ridge between two representatively growing plants in the centre of the plot.

The air temperature and relative humidity were measured every 10 min (*i.e.*, $t = 6*24 = 144$ times per day) at 15 cm above ground in $p = 2$ periods of $d = 14$ days, with period 1 from 24 May 2002 (shortly after mulching) to 7 June 2002 and period 2 from 23 June to 7 July 2002, the last date being the time of approximately maximum crop cover (ca. 80 %).

Data processing was done in three steps. First, for each Hobo logger pair, the differences at each of the $p*d*t = 4032$ times between mulched and unmulched plots were calculated and averaged over all blocks. Second, a two-hourly moving average was applied to these differences in order to smooth the data. Third, using these smoothed differences, the average for each time of the t times of the day, within each of the two 14-days-period was calculated, in order to establish the development of the mulch effect on microclimate depending on the time of the day. Standard errors refer to the variation between days within each period with constant time of the day.

7.2.3 Late blight and black scurf assessments

Assessment of late blight severity was done in five field experiments by estimating the percentage of infected leaf tissue in one to four sample areas of 3 x 3 m per plot from the onset of infection until complete haulm death in intervals of one to two weeks (Table 3). The disease development was summarised by calculating the relative area under the disease progress curve (RAUDPC = the area under the disease progress curve divided by the number of days between first and last disease assessment) for each experiment.

Black scurf severity of harvested tubers was assessed in nine experiments. After partitioning the harvested tubers into three lots (<35 mm, 35-55 mm and >55 mm) with a Schmotzer shaking-grid sorter, 19 – 30 tubers per subsample were chosen randomly from the middle fraction. The number of plots (replications) per treatment, the number of subsamples per plot and the number of tubers per subsample are summarised in Table 4. Tubers were thoroughly washed and then assessed with a key (Lyre, 1982), classifying the tubers into five classes according to the percentage of the tuber area infested with sclerotia: 0 %, 1-4 %, 5-9 %, 10-14 % and ≥15 %. A disease severity index i_{Rs} was calculated using the following equation:

$$i_{Rs} = \Sigma n_j c_j / N$$

where c_j = the lower limit of the j^{th} infestation class, n_j = number of tubers in the j^{th} infestation class, and $N=\Sigma n_j$. The possible maximum of i_{Rs} is 15 %. As a measure of disease incidence the percentage p_0 of uninfested tubers was chosen ($p_0 = \Sigma n_0/N*100$). Both indices were calculated per plot (not per subsample).

Table 3: First and last date, number of assessments, and number of subsamples for assessment of disease severity of *Phytophthora infestans.* Further details for experiments see Table 2.

Exp.	first date	last date	no. of assessments	subsamples
1	21.06.	06.08.	6	1
2	21.06.	06.08.	6	1
4	13.05.	21.08.	6	1
6	25.06.	22.07.	3	4
9	02.06.	28.07.	7	2

Table 4: Number of replications, subsamples und tubers for assessment of infestation with *Rhizoctonia solani* sclerotia. Further details for experiments see Table 2.

Exp.	replicates (plots) per treatment	subsamples per plot	m harvested per subsample	Tubers per subsample
1	8	5	3	20
2	8	11	9	19
3	3	11	9	20
4	8	5	3	23
5	4	5	3	22
6	4	5	3	25
7	4	5	3	25
8	16	4	3	25
9	4	7	3	30

7.2.4 Statistical analysis

Statistical analyses were performed with SAS v6.12 (SAS Institute Inc., 1989; SAS Institute Inc., 1990). Percentage values were arcsin-square-root transformed before ANOVA. (GLM) Untransformed data are presented.

7.3 Results

7.3.1 Microclimate

In the first fortnight period shortly after mulching, the air temperature within the potato stands was higher in the mulched plots than in the unmulched plots during the day (roughly between

7:00 and 17:00 h), but lower in the mulched than in the unmulched plots during the night (Fig 1). Whereas the nightly cooling effect of mulch was also observed four weeks later in the second period, the effect of higher air temperature caused by straw mulch during the day was less marked in the second than in the first period. For both periods however, temperature differences were generally low, amounting to a maximum positive difference of +0.44 K (at 11:30 h, period 1) and a maximum negative difference of –0.42 K (at 18:30 h, period 2).

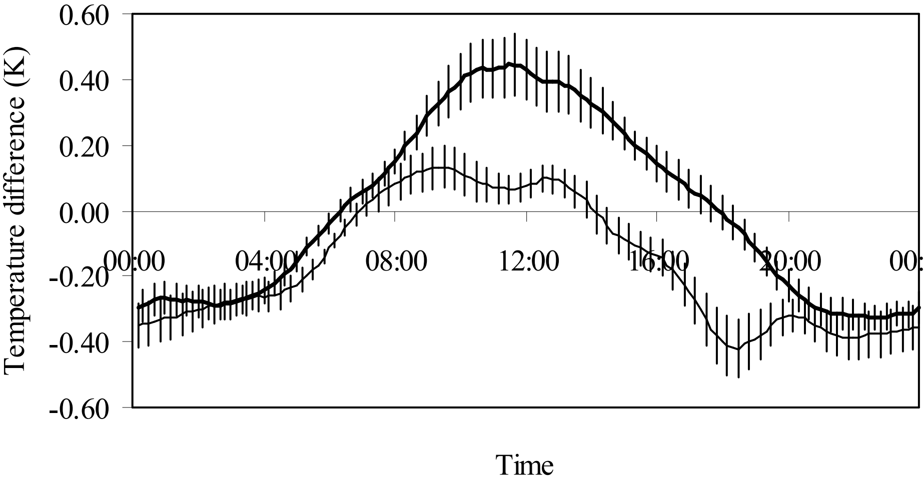

Fig 1: Effect of straw mulch on air temperature in potato stands shown as the temperature difference (M_1-M_0) between mulched (M_1) and unmulched treatment (M_0). Bold line: directly after mulching: fine line four weeks later (dates see text); means ± SE.

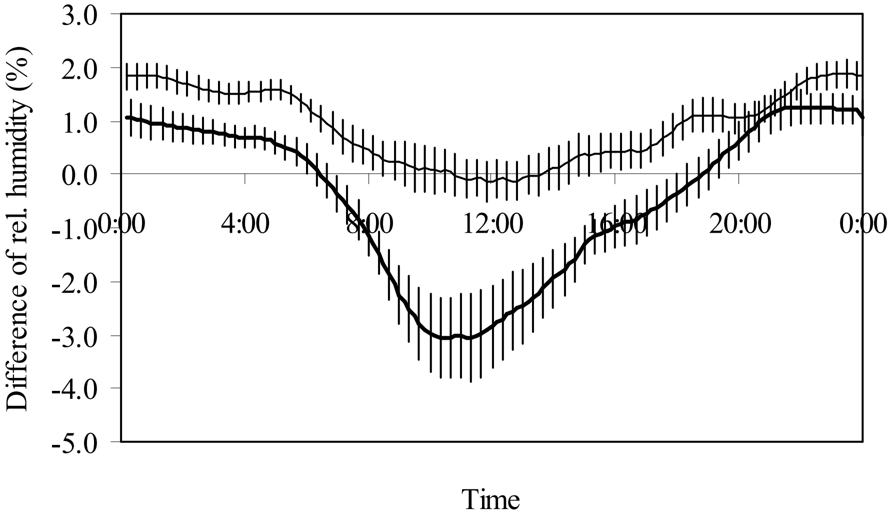

Fig 2: Effect of straw mulch on relative air humidity in potato stands shown as the humidity difference (M_1-M_0) between mulched (M_1) and unmulched treatment (M_0) treatment. Bold line: directly after mulching: fine line four weeks later (dates see text); means ± SE.

The effect of mulch on relative humidity showed a similar picture, but with reversed sign (Fig 2). In the first period, the air within the potato stands was dryer during the day (maximum negative difference of –3.1 % at 10:30 h), but moister during the night (maximum positive difference of 1.2 % at 21:50 h). In the second period, effects during daytime were levelled out with no significant difference between relative humidity in mulched and unmulched plots. However, night time differences were even greater than in the first period, with the mulched plots being moister (maximum difference 1.9 %, at 23:30 h).

7.3.2 Late blight

Late blight severity varied greatly between experiments Although mulching had no significant effect on late blight severity in any of the experiments, a consistent trend was observed over all five experiments, *i.e.* means of relative area under disease progress curve were generally lower in mulched than in unmulched plots (Table 5). In all experiments, spatial effects on late blight were obvious, with significant block effects in experiments 1, 2 and 4.

Table 5: Effect of straw mulch on severity of late blight (*Phytophthora infestans*), measured as relative area under disease progress curve (RAUDPC), over five field experiments.

Exp.	Variety	Year	Error-df	Unmulched	Mulched	Difference[a]	LSD[b]	Block effect
1	Christa	2002	9	0.282	0.264	-0.018 ns	0.101	***
2	Nicola	2002	9	0.027	0.023	-0.004 ns	0.007	***
4	Nicola	2002	7	0.074	0.072	-0.003 ns	0.005	**
6	Marabel	2003	3	0.049	0.030	-0.019 ns	0.047	ns
9	Christa	2004	3	0.135	0.099	-0.037 ns	0.069	ns

[a]: significance level of the difference for the angle-transformed data; differences were not different with untransformed data either.

[b]: Least significant difference (LSD) at p=0.05 for untransformed data;

**: p <0.01; ***: p<0.001.

7.3.3 Black scurf

The infestation of tubers with sclerotia of *R. solani* was not influenced consistently by straw mulch application (Table 6). In seven out of eight experiments there were no significant differences between the infestation of tubers from mulched and unmulched plots, regarding both the disease severity index and the percentage of uninfested tubers. Also, there was no consistent trend of differences. More heavily infested tubers from the mulched plots than from the unmulched plots, *i.e.*, positive differences, were found in four experiments and negative differences in five experiments. There were no significant block effects, except for experiment 4, variable "uninfected".

Table 6: Effect of straw mulch on tuber infestation with *Rhizoctonia solani* sclerotia, expressed as disease severity index i_{Rs} and percentage of uninfected tubers p_0.

		Means *R. solani*-Index				Means "uninfected"			
Exp.	Error-df	Unmulched	Mulched		LSD[a]	Unmulched	Mulched		LSD[a]
1	9	0.13	0.13	ns	0.12	94.8	94.9	ns	3.5
2	9	1.97	2.71	*	0.70	46.4	35.0	*	9.9
3	2	2.33	0.82	ns	3.00	45.7	68.3	ns	36.0
4	7	0.11	0.13	ns	0.17	96.6	95.1	ns	5.6
5	3	0.27	0.18	ns	0.41	90.3	95.4	ns	10.4
6	3	1.60	1.94	ns	2.38	65.7	60.9	ns	44.2
7	3	1.91	2.20	ns	1.10	53.5	52.7	ns	21.4
8	21	1.04	1.04	ns	0.36	74.8	70.4	ns	8.1
9	3	1.43	1.19	ns	0.92	52.0	54.5	ns	29.7

[a] LSD at $p=0.05$ for untransformed data; significance level for angle-transformed data;

*: $p<0.05$.

7.4 Discussion

7.4.1 Microclimate

Straw mulch is known to increase soil moisture by reduction of evaporation (Russel, 1940). In the first few weeks after mulching this effect is likely to be responsible for lower air humidity and increased air temperature during day time. On the other hand, soil temperature during the night was shown to be higher under straw mulch than with unmulched soil (Musso, 1932), which would explain higher relative humidity during night in mulched plots. In addition, mulching decreased the absolute humidity during the night (data not presented). Therefore, the increase of relative humidity at night caused by mulching is mainly due to lower air temperatures. A further possible reason for increased air humidity may be a higher extent of dew formation (Jacks et al., 1955, p. 22).

7.4.2 Late blight

Infections of *Phytophthora infestans* greatly depend on high humidity (Stevenson 2001). Although infections are more likely to take place during night than during day, the moister nocturnal microclimate in mulched potatoes did not lead to higher disease severity. On the contrary, the overall trend was a disease reduction by mulching, although this effect is not significant in any case, when the experiments are considered singly.

The prevailing weather conditions in exp. 9 (frequent and heavy rains during summer) indicate that the interaction of straw mulch with rain splash dispersal of the pathogen could be responsible for a possible reduction of disease severity. The variety used in this experiment (Christa) tends to "lay down" more than the other varieties used (like, *e.g.*, Nicola) that have a more upright plant architecture (Bundessortenamt, 2003); therefore, in more horizontally growing varieties like Christa rain splash dispersal may be of greater importance than in the other varieties. Straw mulch that is known to greatly reduce the impact of rain drops on the soil (Borst & Woodburn, 1942b) may have impeded rain splash dispersal of late blight.

Finally, differences in the plant nutritional status between mulched and unmulched may influence late blight severity. *Phytophthora infestans* is known to respond positively to the nitrogen content of the potato leaves (Carnegie and Colhoun, 1983). Although at present there is no direct evidence for reduced nitrogen content in leaves of straw mulched potatoes, in two experiments presented by Döring and Saucke (2004) and Döring et al. (2004), plants from straw mulched plots were measured with Hydro-N-Tester (Neukirchen and Lammel, 2002) to be less dark green (more yellow) than from control plots, indicating a possible decrease in susceptibility to late blight.

7.4.3 Black scurf

Black scurf is influenced by many parameters, *e.g.* benefitting from high humus content, high weed infestation, and straw incorporation of the pre-crop. Disease levels are also highly dependent on presence and abundance of antagonists like *Verticillium biguttatum* in the soil (Radtke et al., 2000). Although straw mulch is known to influence soil physical and chemical parameters and soil microbial populations (Jacks et al., 1955), it did not affect black scurf.

In arable farms with a potato crop following winter wheat, straw is not recommended to be incorporated into the soil after wheat harvest, because the generalist fungus *R. solani* which survives on plant debris over winter may benefit from this practice and the risk is increased that emerging potatoes are infected by *R. solani*. For this reason, the application of straw mulch after the emergence of potatoes is considered as a strategy for reconciling the aims of plant protection (regarding *R. solani*) and the closed cycle principle (regarding soil organic matter). The fact that straw mulch was neutral to late blight and black scurf in this study is seen as an important factor for the acceptance of this cultural technique.

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8 Synoptic discussion

In the previous five chapters the application of straw mulch in organic potatoes has been investigated from different views: a) the effect on PVY and its vectors; b) the possible mechanisms involved; c) the impact on agronomic parameters, principally yield, nitrate dynamics, weeds and soil erosion; and d) the effect on two fungal potato diseases.

With this background, this last chapter aims to discuss two main questions: (1) How can the application of straw mulch be optimised? (system optimisation). This question is discussed under the aspects of PVY control, compatibility with mechanical weed control, and the technical aspects of straw application. (2) Under which circumstances can straw mulch be recommended for (organic) potato growers? (general system evaluation). This is discussed in the final section, regarding the aspects of plant protection and agronomy presented in the previous chapters.

8.1 Evaluation and optimisation of straw mulch for PVY control

8.1.1 Timing and vector phenology

Straw mulch consistently reduced PVY incidence and vector abundance in a three year study, but there was a high variability between years. This precludes the straw mulch application from a *general* recommendation for seed potato production, whether conventional or organic. However, this may be overcome by specifying conditions for high virus reduction efficiency of mulching. An appropriate tool for this specification is the prediction of vector phenology, *i.e.*, the temporal distribution of vector abundance in a particular year.

Vector phenology strongly influenced the efficacy of both presprouting and mulching with respect to their effects on PVY incidence. At the same time, aphid flight activity generally varies greatly between years, both with respect to the total number of vectors and the time of the peak activity (Fittje et al., 2003). For the improvement of virus control it would therefore be desirable to find possibilities of predicting vector phenology. If it were possible to predict whether vector flight will be concentrated early in the year (spring flight) or later (summer flight), this information – when provided sufficiently early before crop emergence –could be used for appropriate treatment decisions (mulching or presprouting, resp.). On the other hand, combining presprouting with mulching results in relatively high independence from vector phenology. However, this will increase production costs.

There have been several attempts to predict aphid phenology or total aphid numbers in a growing season from various input variables. In general, there is a positive correlation between winter air temperature and number of aphids in the following spring or summer. *E.g.*, the number of alate *Sitobion avenae* caught in a suction trap in England before the end of wheat flowering was negatively affected by the day degrees below 0°C from October to April of the previous winter (Dixon, 1985).

For the region of Bologna (Northern Italy), Rongai et al. (2000) developed a multiple linear regression model for predicting the total yellow pan trap catch of some important PVY vectors until 31 May, from minimum temperatures of December and January; winter precipitation; wind speed in November; and the number of frost days in November. Although significance levels for single input variables were not given, and the model was not validated with independent data, it can be concluded from the regression equations that the number of frost days in November was negatively correlated with the trap catches of *all* species, whereas the other variables did not show consistent results between species. For three different varieties a regression was also calculated between aphid catches until 31 May and PVY incidence in harvested tubers. No significant relationship was found in the less PVY susceptible varieties, but correlation was significant in a susceptible one with low initial virus content.

For New Brunswick, Canada, degree-days (DD) from March onwards were used to simulate time of inflight of *Myzus persicae* into yellow pan traps in potato fields (Boiteau and Parry, 1985). With a thermal summation of 1188 DD, years of early flight could be successfully identified.

Parker (1998) developed a multiple linear regression model for simulating the aphid populations of *M. persicae* and *M. euphorbiae* on potatoes in England and Wales. The timing of the peak population was found to be significantly delayed by lower mean air temperatures in January to March (-4.1 and -2.6 d/°C for *M. persicae* and *M. euphorbiae*, resp.) and by lower temperatures in May (-5.2 and -4.1 d/°C, resp.).

Apart from weather data, aphid population or trap counts from the previous year have been used to explain or predict the population development in the following year (Dixon, 1985), with aphid populations negatively correlated to the previous year´s population, particularly high spring populations of *Aphis fabae* following low autumn populations. Corresponding to these findings, Bagnall (1991) concluded from field trials in New Brunswick that there is generally a biennial cycle in PVY epidemics. In line with this suggestion, in the present study (chapter 2) and subsequent field experiments (Döring, 2004), there was an alternation between high (2000, 2002) and low (2001, 2003) PVY incidence.

These cases demonstrate that the forecasting of aphid inflight from weather data or other parameters is principally possible and can be used to improve decisions on the appropriate virus control strategy (*e.g.*, mulching). However, at present there are not enough data to develop a sufficiently reliable forecasting model for the purpose of mulch optimisation. Moreover, it should be noted that the application of straw mulch may be generally limited in regions where PVY spread usually occurs not before the plants have reached their maximum height. This was observed in a four year study in New Brunswick (Boiteau et al., 1988; but see Bagnall, 1991).

8.1.2 Mulching material

A further approach that appears to be possible for the optimisation of straw mulching for vector control, is the optimisation of the mulching material. However, the choice of the parameters appropriate for optimisation depends on the mechanisms behind the effect of straw mulch on the vectors. Several hypotheses for these mechanisms can be considered (Chapter 4 and 5). Strong evidence for the interference of straw mulch with host finding behaviour was presented in chapter 5 and this may form the basis for optimisation. Within the proposed mechanisms based on optical stimuli, there are three different approaches:

1. Short wavelength hypothesis. "The effect is caused by the repellency of short wavelength light to aphids". It was believed that the reason for the repellency of aluminium and white mulches is the high reflectance of the material (Zitter and Simons, 1980), especially in the short wavelength band (Moericke, 1955; Simons, 1982; Gibson and Rice, 1989). This hypothesis implies that straw mulch reflects more energy either in the UV or in the blue region than soil. It was shown in chapter 4 that straw mulch is almost identical to soil in the UV, but reflexion in the blue region may play a role. At present it is not possible to decide whether this might be an appropriate parameter for optimisation without the knowledge about aphid colour receptors.
2. Contrast hypothesis. "The contrast (colour difference) between soil and plant is reduced by the straw cover and leads to a lower rate of host contacts". Although this hypothesis was often stated to explain effects of *e.g.*, intercropping on aphid infestation of crops, until now there is no direct physiological evidence for the 'reduced' colour difference being responsible for the decrease of aphid numbers. Assuming this mechanism to be mainly responsible for the observed effects on aphids, the optimal straw material would be optically identical to the plant, or, to be more precise, it would not be discernible from a plant by the aphid´s visual system.
3. Attraction and rejection flight hypothesis. "Aphids are (optically) attracted to straw, land on it and probe on it in vain; this induces a strong rebounce of flight, which carries them away from the plant". This hypothesis, suggested and discussed in chapter 5 in detail, has now gained further evidence. In field experiments in 2004, little patches of straw (20 × 30 cm) were spread on soil and covered with black sticky nets (material: see section 3.2.3). This was compared to nets of the same size placed on bare soil. More aphids landed on straw than on soil, indicating that aphids are attracted to straw not only under laboratory conditions (section 5.4) but also in the field. In the case that the rejection flight is mainly responsible for reduced

aphid landing on plants, optimisation would not necessarily involve spectral specifications of the material, but probably its textural traits (smoothness).

Deducing mulch optimisation from the theoretical mechanism is probably too difficult at present; therefore, the empirical (compound) effects of different mulches, as presented in chapter 5, may give hints for optimising the material. One of the interpretations of the results from chapter 5 is that the range of colours that are useful for mulching in terms of reducing aphid infestation or landing is quite large. Within this range there are probably only small differences due to the compensatory effects of contrast and attractivity (apart from backgrounds with high UV reflectances, *e.g.* aluminium). Therefore, the question of (straw) mulch optimisation is probably not answerable by spectral specification, although further studies are required to back a recommendation in this direction. The optimisation of straw mulch for vector control by screening various cereal straw types and textures could be subject to further investigations, and there is considerable variability of straw colour caused by variety, environment and cropping practice (Milatz, 1970). However, because of the different availability of the material, recommendations should not greatly limit the range of cereal species, let alone varieties.

Other parameters appear to be more useful for optimisation. (1) The percentage covered by straw per amount of straw applied; this depends on the piece length of the straw (chapter 6). Therefore, when straw is spread mechanically, brittle straw should be used. (2) the suitability for machinised spreading. Practical own experience from field experiments indicates that straw should be (stored) dry if it is to be spread by machine.

In the case of the optical properties of straw being important for its vector and virus reducing effect it would be necessary to follow these traits over time. Already McCalla (McCalla, 1943; McCalla, 1944) measured light reflection (in foot candles) of straw and found that straw decomposed for 1-2 months was darker than undecayed straw. This was confirmed with spectral measurements of decaying straw applied at 500 g m^{-2}. Therefore, unless straw does decays too quickly after mulching, *i.e.* before the crop cover is closing, this darkening is probably not an obstacle for sufficient optical effects of straw mulch.

8.1.3 Straw mulch in certified *vs*. saved seed potatoes

For the adoption of straw mulch in potatoes for virus control, two scenarios are possible, (1) certified seed potato production for sale; and (2) uncertified seed potato production with harvested tubers to be utilised on-farm by the farmer as seed in the following year (saved seed). In scenario 1, straw mulch is applied to potatoes and the harvest is sold as certified seed if possible. Since mulching did not increase virus content in any experiment, three cases are assumed to be possible in this scenario, regarding the certification of mulched and unmulched potatoes: a) mulched certified, unmulched rejected; b) mulched and unmulched certified; and

c) mulched and unmulched rejected. Case a) is called "successful case", because there, mulching leads to certification, whereas non-mulching would have lead to rejection. A prominent result of chapter 3 was the large variability of the straw mulch effect on PVY incidence. The reduction efficiency ranged from –14 % to –51 % and subsequent field experiments (Döring, 2004) did not show higher reduction. With the seed lot rejection level of 10 % virus, it is easy to see that for a successful case in this scenario, the virus level in unmulched potatoes is required to be within a very narrow range of 11-20 % virus infection, assuming the maximum observed reduction efficiency of 51 %.

For saved seed potatoes (scenario 2) however, requirements are obviously less strict. In this scenario, straw mulch is applied to potatoes in one year; a part of the harvest is used as seed tubers for the following year on the same farm. Assuming that secondarily virus infected plants yield 50 % of healthy plants (see section 2.2.2), already a virus reduction of 10 % would mean a yield gain of 5 % caused by mulching in the preceding year. As there are no strict threshold infection levels for the farmer´s decision whether to save the seed or to buy new certified for the next year, the range of virus infection level in unmulched potatoes is probably larger than in scenario 1.

8.2 Weeds and weeding

The chapters 3 and 6 outline the conflicting requirements of weed control on the one hand and of maintaining an intact mulch cover for vector control on the other. Three strategies appear to be possible to increase the compatibility of straw mulching with mechanical weeding:

(1) Mechanical weeding is done before mulch application, mulch is applied early and weeding is done again later after mulching, when the crop canopy is covering most of the soil and after the flight peak of vectors. Here, weeding cannot be done too late because the larger plants are injured by the machinery. Therefore, unfavourable (rainy) weather before the optimum weeding time, the optimum being determined by vector phenology and crop size, may limit this strategy. Under favourable soil conditions (dry soil) however, the mulch layer will not be destroyed by incorporation into the soil during the weeding process but the straw will stay on top of the soil. This effect was observed in a field experiment with two replications at Hebenshausen in 2001.

(2) The amount of straw is considerably increased to achieve weed suppression. As found in chapter 6, there was no significant and consistent effect of straw mulching on weeds with the relatively low amounts applied. This approach is only economical if the reduction in the number of weeding treatments (over)compensates the increase in costs for straw material and spreading. Moreover, larger amounts may negatively affect the harvesting process.

(3) All mechanical weeding is done before mulch application. A possible limit to this approach is set by unfavourable weather conditions, especially on loamy soils: if rain

alternates with sunny periods in spring, the soil will be too wet to do the last mechanical weeding early, so that mulching is delayed, but at the same time the vectors will leave their winter hosts. This results in a high flight activity before the protection of the crop by mulching is possible.

In all on-farm trials within a project in three main potato growing areas (Döring, 2004), farmers tended to adopt the last strategy. One of the reasons for this is probably that the effect of weeding is very obvious and clear whereas the effects of straw mulch (regarding virus control and nitrate loss reduction) are less obvious, not well established in the farmers′ view, and subject to considerable variability. So, mulching would not be applied before the last weeding is done. The risk of delayed mulching can, however, be reduced by decreasing the number of mechanical weeding treatments while other approaches are adopted in order to keep weed levels below the economic injury level (*e.g.*, changes in the crop rotation).

A further aspect of mechanical weeding in potatoes with straw mulch application is the type of machine used for weeding. If the machinery builds up high ridges with a steep shoulder, two undesired effect occur: the straw accumulates in the furrows; and the amount to cover the soil is increased. Therefore, for an optimal mulch cover, machinery should be used that produces a relatively flat ridge (*e.g.*, with ridging disks).

8.3 Evaluation and optimisation of straw spreading machinery

Two types of straw spreading machinery were used in the on-farm field experiments: The Kverneland Round Bale Shredder KD 807 (Figure 1, next page) and the Hawe Stable Straw Spreader (Figure 2 and 3). The spreading procedure was evaluated with two parameters: (1) the time used to spread straw onto a given area; this had to be extrapolated from the relatively small experimental plots. (2) the precision in directing the straw and achieve an even distribution. Regarding both parameters, the Hawe machine was clearly superior. Positive experience in mulching potatoes with other machinery (Baas stable straw spreader and Tomahawk straw chopper) was reported by Thieme (2004, pers. comm.) and Heimbach (2004, pers. comm.). According to Padel and Dreyer (1993), the labour time spent in organic potato production is around 170–200 h ha^{-1}. From the application with a Hawe Stroh spreader in the field experiments it was calculated that 3.5 h ha^{-1} are required for mulching.

Straw mulch application is an optimal tool for soil erosion control as shown in chapter 6. Since long straw is less effective in soil erosion control than cut material, the straw mulch application can be optimised economically by using a straw spreader that cuts the material or straw that is brittle enough to result in relatively small pieces when spread with a non-cutting machine.

Figure 1. Kverneland Round Bale Shredder KD 807, spreading straw to potatoes

Figure 2. Hawe Stable Straw Spreader at straw mulch application

Figure 3. Field experiment with mulched potatoes, straw spread with the Hawe machine, 2004

8.4 Summarising system evaluation

The prospect for the adoption of any measurement in agriculture does not only depend on its "efficiency" to mitigate a certain problem, but also on the severity of that problem relative to the importance of other problems. Following a survey in seven European countries (Tamm et al. 2004), farmers consider *Phytophthora infestans* as the most important plant health problem in current organic potato growing. *Rhizoctonia solani* and *Streptomyzes scabies* are mentioned as the second and third most important problem, respectively. For neither of these major diseases straw mulch has the potential to contribute to a reduction (chapter 7; Döring 2004). On the other hand, straw mulch did not aggravate these problems, which is considered to be an important requirement for the acceptance of this technique. Following the strength and variability of straw mulch effects, recommendations for mulch application can be specified with respect to space and time as follows.

(1) Straw mulch is an appropriate tool for the control of soil erosion on sloping fields with silt or clay soils. The soil protection effect of straw mulch is drastic, reliable, and occurs already at low mulch quantities. However, already at the farm level, the economic evaluation of this effect is very difficult. Moreover, regarding the costs of soil erosion it is necessary to take into account higher (spatial) levels beyond the farm. Therefore, the application of straw mulch for soil erosion control requires the farmer to adopt a long-term oriented resource protection view. This appears to be difficult as the profitability of organic potato growing is expected to decrease in the next years (Tamm et al., 2004).

(2) On sandy soils with the risk of nitrate leaching, straw mulch may contribute to the reduction of post-harvest nitrate losses. This is of economic relevance especially when farming in ground water protection areas, where subsidies are cut if nitrate levels in the ground water exceed threshold levels. In very early potatoes, there is presumably enough time to establish a green manure to bind the soil nitrogen mineralised at harvest. Therefore, the mulch application appears to be more appropriate with later varieties. However, there are currently no studies known to the author that deal with straw mulch effects on nitrate dynamics in later varieties.

(3) For the control of potato virus diseases, straw mulch is particularly appropriate in years with a distinct spring flight peak (following mild winters), especially when susceptible varieties are used. Following the considerations in section 8.1.3, mulch application will probably be more appropriate for saved seed potatoes than for certified seed.

One of the most important questions that must remain unanswered in this thesis is whether the application of straw mulch in organic potatoes can be recommended from an economic viewpoint.

An evaluation of straw mulch regarding the principles of organic farming (IFOAM, from Lampkin, 1994, p. 4), comparing it to an organic potato production system without straw mulch, reveals that (1) straw mulch application follows the aim "to use as far as possible renewable resources in locally organised agricultural systems", because it is usually locally available, at least on arable farms; (2) the approach works "within a closed system with regard to organic matter and nutrient elements", as straw is re-applied to the soil as a source of organic matter; N losses and soil erosion are reduced; (3) it "avoids all forms of pollution that may result from agricultural techniques", since post harvest N losses can be reduced; but (4) it is possibly in conflict with the aim "to give all livestock conditions of life that allow them to perform all aspects of their innate behaviour". Straw as an optimal bedding material for animal husbandry is sometimes scarce on livestock farms and animal welfare was assessed to be better in housing systems where a higher quantity of straw was applied (Hörning, 2001). However, on arable farms there is usually not a severe shortage of straw.

Concluding, the application of straw mulch in potatoes is an environmentally sound measure that can contribute to improved plant health and reduced environmental costs of agriculture. The prospect for its adoption does not only depend on its further optimisation but also on the willingness of society to pay for agriculture that is ecologically sustainable.

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Annex

Numbering of field experiments

Table A1: Numbering of field experiments throughout the chapters

Experiment			Chapter				
Year	Site[a]	Variety	3	4	5	6	7
2000	H	Christa	A	1			
2001	N	Christa	B			1	
	N	Marabel	E			2	
	N	Rosella				3	
2002	N	Christa	C			4	1
	N	Nicola	D			5	2
	E	Christa		2		6	3
	E	Nicola		3		7	4
	E	Nicola				8	5
2003	N	Marabel		4		9	6
	N	Rosella				10	7
	E	Christa		5		11	9
	E	Nicola		6		12	8
2003	H	(green traps)					
	H	(sticky sheets)					
2004	N	Marabel		7			
	N	Simone		8			
	E	Christa		9			
	E	Nicola		10			
	E	Nicola		11			
2004	H	(green traps)		*			

[a]: H: Hebenshausen; N: Neu-Eichenberg; E: Etzenborn (N & H = "site A" and E = "site B")
*without number

Virus diagnosis

PVY diagnosis was done with DAS-ELISA (Double Antibody Sandwich - Enzyme-Linked Immuno-Sorbent Assay). This test was introduced to plant virology by Clark and Adams (1977), and is now common practice in the official certification programs (Casper and Meyer, 1981; Torrance, 1992; Kegler and Friedt, 1993). The procedures applied in the presented study followed the current practice in the laboratory for seed potato certification in Hessen, Germany (Pflanzenschutzamt Wetzlar). As virus diagnosis of sap obtained directly from harvested tubers is not reliable, plantlets were grown from tubers. To this end, half-spheres of ca. 1 cm diameter containing one or more eyes were cut from the tuber. For dormancy breaking these were bathed for 15 min (2000 and 2001) or 10 min (in 2002 and 2003) in 1 ppm gibbeleric acid; the eyes were dried for one day at room temperature and planted in a mixture of ca. ca. 45 vol-% unfertilised standard growing substrate (EE0), ca. 45 vol-% commercial potting earth and 10 vol-% sand. The eyes were grown in aphid free greenhouse chambers / temperature. Two to eight weeks after emergence, leaf sap was obtained by grounding one leaf picked from the middle part (Krause et al., 2003) of each plantlet. Non-strain-specific, polyclonal PVY antisera (obtained from BIOREBA, Switzerland) were used to ensure that all PVY strains were detected. The composition of buffers and a detailed protocol for the ELISA procedure are given in the annex (A.1). In the current certification practice, the colour reaction in the microplates is analysed by quantitative measurement (extinction at 405 nm); in the present study, however, qualitative measurement (virus present / virus not present) by assessment with the unsupported human eye appeared to be sufficient for the purposes of this (epidemiological) study. Ambiguous samples were extremely rare; these were tested a second time. In 2000 one tuber from each selected plant was tested. In secondarily infected plants all tubers are infected (Krause et al., 2003).

Table A 2: Composition of buffers for ELISA procedure

Name of buffer	Ingredient	Amount for 1000 ml	Unit
Coating buffer	Na_2CO_3	1.590	g
	$NaHCO_3$	2.930	g
	NaN_3	0.2[a]	g
Washing buffer concentrate (WPC)	NaCl	80.0	g
	KH_2PO_4	2.0	g
	Na_2HPO_4 x 2 H_2O	14.4	g
	KCl	2.0	g
	NaN_3	2.0[a]	g
	NaOH	add to achieve pH 7.4	
	Tween 20	5.0	ml
Washing buffer	WPC	100	ml
Sample buffer	WPC	100	ml
	Polyvinylpyrrolidone	20.0	g
Conjugate buffer	WPC	100	ml
	Polyvinylpyrrolidone	20.0	g
	Egg albumine	2.0	g
Substrate buffer	Diethanolamine	97.0	ml
	NaN_3	0.2[a]	g
	HCl	add to achieve pH 9.8	

[a]: from 2003 on, the amount of this preserving agent was reduced to half due to its high toxicity

Table A 3: Detailed protocol for ELISA procedure

Preparations Setting up of machines
Leaf sap mill 400 V / 50 Hz, Meku Pollähne
Electronic buffer adder 230 V / 50 Hz

1 Coating

1.1 Dilute antibody (PVY-IgG) 1 : 1000 in coating buffer (1µl/1ml)

1.2 Fill 100 µl of coating solution per cavity into ELISA-plates (NUNC Maxisorp with 96 cavities (wells)) (=9.6 ml per plate)

1.3 Incubate for 4 h at 35 – 37 °C; cover the plated with a spare plate to reduce evaporation. Place a jar of water into incubator to achieve higher air moisture.

1.4 Pour out coating solution. Wash the moist plates by filling plates with washing buffer, waiting for 3 min., and pouring out washing buffer. Repeat washing 3 times (or 2 times, see 1.5). Make plates half-dry by beating onto paper towel.

1.5 Ad libitum: freeze plates after second washing, store 2 – 4 months

2 Add the sample

Table A 2 continued.

2.1 Homogenise leaf to obtain leaf sap with leaf sap mill; add 1.35 – 1.50 ml sample buffer; after each sample cleanse leaf mill with tap water for 4 to 5 sec. Store samples not longer than 1 h at room temperature, if longer time is needed before step 2.2, store samples at 4°C. Do not wait longer than 36 h before step 2.2.
2.2 Fill 100 µl of sample leaf sap per cavity into coated and freshly washed and half-dried ELISA-plates.
2.3 Incubate over night (for at least 12 hrs) at 4°C.
2.4 Washing: Beat out leaf sap, fill in washing buffer with high pressure and directly pour it out. Wash again two times as described in 1.4.

3 Add the conjugate
3.1 Dilute conjugate (polyclonal PVY IgG conjugated with alkaline phosphatase) in conjugate buffer 1 : 1000 (1µl/1ml).
3.2 Fill 100 µl of conjugate solution per cavity into washed and half dry (2.5.) plates.
3.3 Incubate for 4 h at 35 – 37 °C; with one plate as a cover. Place a jar of water into incubator
3.4 Wash (as described in 1.4)

4 Add the substrate
4.1 Dilute substrate (p-Nitrophenylphosphate) 1 : 1000 in substrate buffer (1mg/ml)
4.2 Fill 100 µl of substrate solution per cavity into freshly washed and half-dried plates
4.3 Incubate 1h (to 2 h) at room temperature; do not expose to direct sun light.

5 Assessment
Read out reaction on plates

Additional experiment (from chapter 5)

In order to find out whether straw mulch is visually attractive to aphids, an experiment was carried out in a transparent wind channel (42 cm by 100 cm ground area, 42 cm height; air temperature constant at 23°C, relative humidity at 75 %, laminar wind at 0.24m/s), excluding any possible olfactory cues. The arena was illuminated by four 65 W chrome light tubes. A dark brown, shallow plastic pan of 23 cm diameter was filled with top soil from the field experimental site and placed in the wind channel with 38.5 cm distance to the wind source and 0.5 cm distance to the observation screen. Wheat straw pieces of 5 cm length were glued to a 5 by 5 cm cardboard. This target was placed in the middle of the pan onto the soil. For observations, aphids were starved and allowed to acclimatise for 3 h. 10 apterae and 1 alata were carefully placed in the middle between the target and the rim of the pan, so that the longitudinal body axis was at 90° to a thought line between target and rim and the target was lee from the aphid.

Behaviour of the aphids was classified into the following categories: movement (walking) to the target, movement away from the target, movement without change of distance to the target, no movement, and probing (holding antennae over dorsum, no movement of legs and placement of the proboscis onto any surface). The time of any behavioural change was noted in seconds. The experiment was stopped for each aphid after 10 min.

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Use of data transformation in agricultural research

Abstract

Data transformation prior to the performance of analyses of variance and backtransformation of obtained means are often recommended in textbooks of biometry and applied statistics. The frequency of such transformations and subsequent procedures in scientific agricultural literature was determined considering a total of 120 papers from two international journals. Half of the 30 papers where transformation was performed did not mention the aim or effect of transformation. The presentation of untransformed data was more common than of backtransformed data. In a case study analysis of a data set from field research, the presentation of untransformed proportion means was compared to angle-transformed and backtransformed means. Treatment effects appeared to be stronger when proportion values were angle-transformed and backtransformed than when untransformed means were presented. This is shown to be generally the case when proportions are well below 0.5. The consequences of these effects for data presentation are discussed.

Introduction

The non-linear transformation of data is often recommended in textbooks of applied statistics (Sokal and Rohlf, 1995; Sachs, 1999; Köhler et al., 2002) as a tool to achieve approximate normality and homoscedasticity. A further important reason for data transformation has been stated in the fact that – form a theoretical viewpoint – the transformed data are more appropriate to describe certain biological variables, *e.g.* in the case of the square root transformation of organismal surface area (Sokal and Rohlf, 1995). When analyses of variance are performed with transformed data, the presentation of estimates of untransformed means and standard errors does not appear to be appropriate (Gomez and Gomez, 1984), because the obtained F-values and significance levels are only valid for the transformed data. The presentation of transformed data is considered to be disadvantageous because the original scale and dimension are lost. Therefore, it is recommended to present backtransformed data by applying the inverse transformation function to the means of the transformed data. However, it was noted early on that backtransformation of means and standard errors implies bias (Anscombe, 1948). Statistical methods have been developed in order to correct for the bias introduced by backtransformed data (Neyman and Scott, 1960). Another way that was suggested to cope with this bias is the presentation of (asymmetrical) confidence limits around the backtransformed means (Sokal and Rohlf, 1995). Finally, in cases where data transformation appears to be useful, data distributions are often skewed so that the median is more appropriate to describe the data than the mean; as backtransformed data are estimates of the medians on the original scale, but not of the means, it was suggested that generally backtransformed data should be presented in combination with the explicit statement that these are estimates of the medians rather than the means (*cf.* Connolly & Wachendorf, 2001). The aims of this paper are (1) to elucidate the usage frequency of data transformation and of the above mentioned subsequent procedures after transformation, within the field of agricultural research (survey); and (2) to compare presentation of untransformed and backtransformed data in selected data sets for differences in their statistical results (case study).

Material and Methods

Survey

In order to determine the usage frequency of data transformation in association with analyses of variance (ANOVA), and of the subsequent statistical procedures, papers with ANOVAs were chosen from the years 1992 and 1997, published in two highly acknowledged international journals dealing with agricultural research, with journal A covering agronomy and journal B covering phytopathological aspects. For each journal and each volume, 30 papers were chosen systematically, *i.e.* starting from the first page of each volume and following up in the order of appearance of the papers. It was noted (1) what kind of data transformation was done (if any); (2) if backtransformed or untransformed means were presented; (3) if corrections for bias introduced by backtransformation were made.

Case study

Two data sets (percentage values, from Döring & Saucke, 2005 and Döring et al., 2005) were subjected to arcsin-square-root-transformations. The Shapiro-Wilk test was performed to test for deviations from normality and the Levene test for heterogeneity of variances (Dufner et al., 1992). Both tests were run with transformed and untransformed data in order to assess transformation efficiency. All statistical calculations were performed with SAS software (SAS Institute Inc., 1989; SAS Institute Inc., 1990).

Results

Survey

Data transformation was performed in 25 % of the papers considered (Table 1); in both years, consistently more cases of data transformation were observed in the phytopathological journal (B) than in the journal dealing with agronomy (A). The most frequent type of transformation was the arcsin-square-root function for proportional data. Half of the papers that performed any transformation did not mention the aim or effect of transforming the data. In some of the surveyed papers the aim was quite unspecific, like the case where, after encountering "mild" heteroscedasticity, "data transformation were not considered to be advantageous". In the majority of papers, untransformed data were presented or no statement was made about the type of presentation. In none of the cases considered, corrections were made for bias introduced by transformation.

Table 1: Usage frequency of data transformation and subsequent procedures in two agricultural journals in 1992 and 1997.

	Journal	A	A	B	B	
	Year	1992	1997	1992	1997	Sum
	Number of papers	30	30	30	30	120
Cases of transformation	total	4	1	13	12	30
	arcsin-square-root	1	0	3	5	9
	log	2	1	4	2	9
	other	1	0	6	5	12
Aim	homosced./stabilise variances	2	0	3	4	9
	normality	0	0	2	0	2
	homosc. & normality	0	0	0	1	1
	biology	0	0	0	1	1
	other	1	0	0	1	2
	none stated	1	1	8	5	15
Data presentation	untransformed	3	0	10	11	24
	backtransformed	1	0	3	0	4
	transformed	0	0	0	1	1
	transformed & untransformed	0	1	0	0	1

Case study

With the data set obtained from Döring & Saucke (2005), angle-transformation of proportion values mostly resulted in higher rejection probabilities with respect to ANOVA assumptions (Table 2a). With untransformed data, "mild" heterogeneity of variances occurred in two out of ten cases (experiments 4 and 7), and in one of these, transformation resulted in the acceptance of homoscedasticity, assuming the usual threshold of $P = 0.1$. With the other data set (from Döring et al., 2005), transformation did not result in a better performance with respect to the assumptions of ANOVA (Table 2b). The comparison of untransformed and backtransformed means following angle-transformation revealed that, in most cases of the first data set, backtransformed means tended to be lower than untransformed ones (Table 3). Considering the relative reduction R by the treatment M_1 with $R = (M_1-M_0)/M_0*100$, calculations from backtransformed means mostly showed stronger reduction values than from untransformed data. Most interesting is the case of experiment 4, where untransformed means were exactly equal (resulting in R=0), while with backtransformed data there was a relative reduction of 35 %; however, the absolute data were very low and therefore, relative reduction values are misleading anyway. In the second data set backtransformed means tended to be higher than untransformed means (Table 4).

Table 2a: Data set 1: Comparison of untransformed and arcsin-square-root-transformed data, regarding the probabilities of deviation from normality and homoscedasticity; data set from Döring & Saucke (2005). Annotations see under Table 2b.

	Normality (P<W)				Homosced. (P>F)[a]		Summary[b]	
Exp.	M=0		M=1					
	untr.	transf.	untr	transf.	untr.	transf.	untr.	transf.
2	0.463	0.465	0.463	0.446	0.458	0.646	OK	OK
3	0.486	0.321	0.719	0.457	0.181	0.410	OK	OK
4	0.000	0.000	0.272	0.196	0.097	0.147	H![c] N![b]	N!; tr >[e]
6	0.273	0.137	0.001	0.079	0.682	0.822	N!	N!; tr >
7	0.000	0.000	0.967	0.992	0.054	0.057	H!	H!
8	0.964	0.958	0.272	0.245	0.574	0.778	OK	OK
9	0.158	0.228	0.026	0.026	0.396	0.411	N!	N!
10	0.272	0.246	0.272	0.123	0.131	0.743	OK	OK
11	0.224	0.247	0.654	0.638	0.113	0.239	OK	OK

Table 2b: Data set 2: Comparison of untransformed and arcsin-square-root-transformed data, regarding the probabilities of deviation from normality and homoscedasticity; data set from Döring et al. (2005).

	Normality (P<W)				Homosced. (P>F)[a]		Summary[b]	
Exp	M=0		M=1					
	untr.	transf.	untr.	transf.	untr.	transf.	untr.	transf.
3	0.636	0.617	0.417	0.434	0.112	0.117	OK	OK
4	0.014	0.064	0.020	0.190	0.657	0.092	N!	N! H!
5	0.969	0.997	0.276	0.174	0.507	0.029	OK	H!
6	0.609	0.533	0.630	0.607	0.190	0.216	OK	OK
7	0.847	0.844	0.744	0.729	0.306	0.309	OK	OK
9	0.345	0.343	0.385	0.340	0.251	0.254	OK	OK

[a] regarding treatment effect

[b] regarding the assumptions of ANOVA (normality and homoscedasticity)

[c] Homogeneity of variances to be rejected (P=0.1)

[d] Normality to be rejected (P=0.1)

[e] Transformation leads to acceptance of homoscedasticity

Table 3. Comparison of untransformed and backtransformed means after arcsin-square-root-transformation of proportion values (from Döring & Saucke 2005). Variable: percentage of aphid infested potato leaves.

	M_0 (unmulched)				M_1 (mulched)				relative reduction R*		
Exp.	transf.	untr.	backtr.	Diff.	transf.	untr.	backtr.	Diff.	untr.	backtr.	Diff.
2	0.759	40.0	47.3	7.3	0.429	17.3	17.3	0.0	-56.7	-63.4	-6.7
3	0.646	36.5	36.2	-0.3	0.412	16.3	16.0	-0.3	-55.5	-55.8	-0.3
4	0.106	1.5	1.1	-0.4	0.086	1.5	0.7	-0.8	0.0	-34.9	-34.9
5	0.000	0.0	0.0	0.0	0.000	0.0	0.0	0.0	0.0	0.0	0.0
6	0.235	6.5	5.4	-1.1	0.130	3.3	1.7	-1.6	-50.0	-69.1	-19.1
7	0.361	12.5	12.5	0.0	0.349	12.5	11.7	-0.8	0.0	-6.5	-6.5
8	0.336	11.0	10.9	-0.1	0.210	4.5	4.3	-0.2	-59.1	-60.3	-1.2
9	0.136	2.0	1.8	-0.2	0.050	0.5	0.3	-0.2	-75.0	-86.3	-11.3
10	0.299	9.0	8.7	-0.3	0.136	2.5	1.8	-0.7	-72.2	-78.8	-6.6
11	0.310	9.5	9.3	-0.2	0.246	6.0	5.9	-0.1	-36.8	-36.6	0.2
median	0.305	9.3	9.0	-0.2	0.173	3.9	3.1	-0.3	-52.8	-58.0	-6.5
min	0.000	0.0	0.0	-1.1	0.000	0.0	0.0	-1.6	-75.0	-86.3	-34.9
max	0.759	40.0	47.3	7.3	0.429	17.3	17.3	0.0	0.0	0.0	0.2

* formula for R see text

Table 4. Comparison of untransformed and backtransformed means after arcsin-square-root-transformation of proportion values (from Döring et al., 2005). Variable: percentage of potato tubers uninfested with *Rhizoctonia solani* sclerotia.

Exp.	M_0 (unmulched)			M_1 (mulched)			M_1-M_0	
	untransf.	backtransf.	Diff.	untransf.	backtransf.	Diff.	untransf.	backtransf.
3	45.7	45.3	-0.4	68.3	68.4	0.1	22.5	23.0
4	96.6	98.5	1.8	95.1	95.6	0.6	-1.6	-2.8
5	90.3	90.7	0.4	95.4	97.7	2.3	5.1	7.0
6	65.7	67.4	1.8	60.9	61.1	0.2	-4.8	-6.3
7	53.5	53.5	0.0	52.7	52.8	0.1	-0.8	-0.7
9	52.0	52.0	0.0	54.5	55.0	0.5	2.5	3.0
median	59.6	60.45	0.2	64.6	64.75	0.35	0.85	1.15
min	45.7	45.3	-0.4	52.7	52.8	0.1	-4.8	-6.3
max	96.6	98.5	1.8	95.4	97.7	2.3	22.5	23

Discussion

Gomez and Gomez (1984, p. 303) state that the presentation of means from untransformed data is more common in practice than the more appropriate use of backtransformation; this was now confirmed with the presented survey of scientific papers. From the papers investigated it cannot be inferred if transformation was done following *general* recommendations or if statistical criteria applied to the respective data were used for the procedure chosen.

Sachs wrote that "it is comforting that analyses of variance calculated with or without transformation are less different in their results than is expected." (Sachs, 1999, p. 634; own translation). However, it should be noted that, in many cases, the choice between the presentation of backtransformed and untransformed data offers the dangerous possibility to make data more "sexy". In the common case of angle transformed proportions, low proportions (well below 0.5 or 50%) tend to be lower when backtransformed than when untransformed (and vice versa with proportions above 0.5) (Figure 1).

The difference between backtransformed and untransformed data increases with the standard error of the mean and with the proportions approaching 0 and 1, respectively. An important consequence of this is that "desired" treatment effects (*reduction* of proportions in comparison to an untreated check), appear to be stronger when presented from backtransformed than from untransformed data. Vice versa, under conditions of high proportions (approaching 1), "undesired" treatment effects (increasing proportions) appear weaker when presented with untransformed data. For this reason the more conservative presentation of untransformed means was chosen in the case study presented.

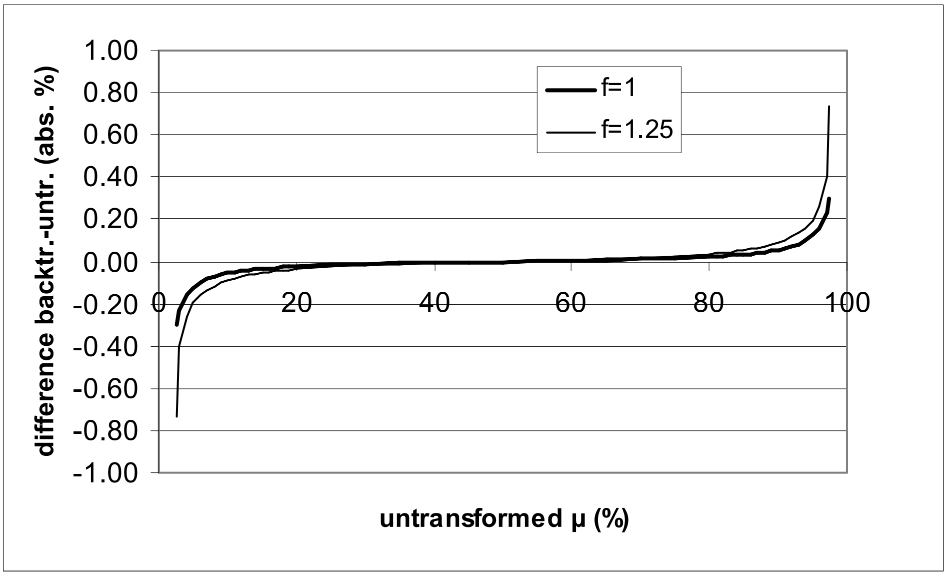

Figure 1: The difference between backtransformed and untransformed means (absolute % difference) plotted against the untransformed mean µ, depending on the standard error. This graph was calculated using n=4 replications. The standard error was chosen to be symmetrical around the mean and constant over the whole scale of µ, with SE = f*0.913, with f_1 =1 and f_2=1.25.

Conclusions

In many acknowledged textbooks of statistics justification can be found for the presentation of both untransformed and backtransformed data. Also, the choice between transformation and non-transformation may seem to be rather free, as there are quite unspecific reasons for transformation, such as the "biology" of the variable or its theoretical distribution (*cf.* Hartung, 1986). As was shown above in the case of the arcsin-square-root-transformation, this implies the possibility of data manipulation. One may draw the conclusion that generally data ought to be shown independent from the transformation, *i.e.* both the analysis of transformed and untransformed data should be shown. However, this approach is limited when more complicated experimental designs are involved. Therefore, in the case of backtransformation it should be explicitly stated that the obtained figures are estimates of the medians and not of the means.

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Erklärung

Hiermit versichere ich, dass ich die vorliegende Dissertation selbständig und ohne unerlaubte Hilfe angefertigt und andere als in der Dissertation angegebene Hilfsmittel nicht bentzt habe. Alle Stellen, die wörtlich oder sinngemäß aus veröffentlichten oder unveröffentlichten Schriften entnommen sind, habe ich als solche kenntlich gemacht. Kein Teil dieser Arbeit ist in anderen Promotions- oder Habilitationsverfahren verwendet worden. Kapitel 3 und 5 der Arbeit sind bereits in Zeitschriften veröffentlicht.

Witzenhausen, den 7. Januar 2005

Thomas Döring