**Master’s Thesis**

# Einfluss der Bodenbearbeitungstechnik auf das Auftreten von Durchwuchskartoffeln

# The effect of post harvest tillage on volunteer potatoes (groundkeepers)

zur Erlangung des akademischen Grades Master of Science (M.Sc.)


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**Eingereicht am** 18.06.2020

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| | |
|---|---|
| **am** | Ante Meridiem |
| **DWD** | German Weather Service (Deutscher Wetter Dienst) |
| **F** | field experiment |
| **GmbH** | limited liability company (Gesellschaft mit beschränkter Haftung) |
| **h** | hour(s) |
| **ha** | hectare |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **LfL** | Bavarian regional office for agriculture (bayrische Landesanstalt für Landwirtschaft) |
| **LWK** | regional office for agriculture (Landwirtschaftskammer) |
| **NRW** | North Rine-Westphalia |
| **pm** | Post Meridiem |
| **U.K.** | United Kingdom |
| **V** | variant |

## Abstract

Volunteer potatoes (*Solanum tuberosum*) are an increasing weed problem in potato rotation, particular after mild winters. The present study tested the effect of tillage on occurrence of volunteer potatoes. The mortality of potato tubers was measured in five field experiments at four sites in Germany in 2019/2020. In autumn manually coloured potato tubers were buried and laid on soil surface. They were treated with six different tillage variants: ploughing, cultivating (three crossings), frost cultivating, disc harrow with serrated discs (two crossings) and no tillage. Subsequently the number of tubers on soil surface after tillage, their status of damage and distribution in soil was evaluated. In spring the germination of the potatoes and the tuber distribution in soil was investigated.

The study shows that no tillage and frost cultivation significantly reduced occurrence of volunteer plants in spring compared to common ploughing. Monitoring of winter soil temperatures and timed frost cultivating could be used to control volunteer plants in subsequent growing season.

## Zusammenfassung

Durchwuchskartoffeln (*Solanum tuberosum*) sind das größte Unkrautproblem in Kartoffelfruchtfolgen, welches mit jedem milden Winter verschärft wird. Die Bodenbearbeitung nach der Kartoffelernte beeinflusst das Überleben der Durchwuchskartoffeln im Boden über Winter. Die vorliegende Masterarbeit untersuchte 2019/2020 in fünf Feldversuchen in vier verschiedenen Bundesländern in Deutschland, welches Bodenbearbeitungsgerät die Durchwuchskartoffeln am erfolgreichsten bekämpft. Für diese Untersuchung wurden Kartoffelknollen unterschiedlich angefärbt im Feld eingegraben und auf der Oberfläche ausgelegt. Anschließend wurde mit den Bodenbearbeitungsgeräten (Pflug, 3x Grubber, Frostgrubbern, 2x Scheibenegge, Fräse mit Winkelmessern, unbearbeitet) bearbeitet. Im Oktober 2019 wurden die Knollen an der Oberfläche, ihr Beschädigungsstatus und ihre Verteilung im Boden bonitiert. Im darauffolgenden Frühjahr wurde die Anzahl an Kartoffelpflanzen und ebenso die Verteilung der Mutterknollen im Boden bonitiert.

Die Ergebnisse der Arbeit zeigen, dass die Varianten unbearbeitet und Frostgrubbern die Durchwuchskartoffeln signifikant reduzieren konnten, im Vergleich zum üblichen Pflügen. Wird die Bodenbearbeitung dementsprechend angepasst, ist es möglich das Problem der Durchwuchskartoffel teilweise zu verringern.

# 1 Introduction

‘The potato is on the frontline in the fight against world hunger and poverty’, by Jaques Diouf, the Director-General of the FAO (2008). Already in 2008, Jacques Diouf pointed out that potatoes (*Solanum tuberosum*) should be a major component in strategies aimed at providing nutritious food for the poor and hungry. Potato is the third most important food crop in the world after rice and wheat in terms of human consumption (Devaux et al. 2014). Worldwide, over the last few decades, potato production has increased at much higher rate compared to other major staple crops (Kreuze et al. 2020, pp. 390). In total, 361 168 914 tonnes of potatoes are grown worldwide on an area of 17 578 672 ha in 2018 (FAOSTAT). In Germany potatoes are the second important crop after cereals in 2019. They were grown on a total area of about 272 000 ha in 2019 which is an increase of about 20 000 ha compared to 2018 (Hambloch 2019). Recently it is assumed that this trend will continue with an accrual of 5 000 ha in 2020. First estimations showed an area of 277 000 ha for potato cultivation in 2020, however, this value was very variable because of the corona pandemic (Hambloch 2020). But an increasing percentage of potato in crops rotation is accompanied by several problems. Especially the weed potatoes or so-called volunteer potatoes (groundkeepers) in the potato gap years have developed into a serious and expensive problem in agriculture.

## 1.1 Definition of volunteer potatoes

Volunteer potatoes, also called groundkeepers, are tubers of the potato (*Solanum tuberosum*) which produce unwanted potato plants in a wide range of cultivated crop species (Askew and Struik 2007). A potential to increase populations as with other weed species, which produce true seed, exists since each plant can produce up to 25 new tubers or rather potato plants. Every tuber turns into a weed potato in the following cultivated crop species. Unlike most other weeds, volunteer potatoes can reproduce in two different ways. Volunteer potatoes can arise vegetative from the mother tuber by remaining tubers on the field after harvesting. Secondly, weed potatoes can be produced from true seeds. In Germany most volunteer potatoes arise vegetative, therefore the following work will focus on remaining daughter tubers in the field.

# 2 The state of art

## 2.1 The hazards of volunteer potatoes in agriculture

Volunteer potatoes pose a serious threat to crop production, since they are highly competitive weed plants and contribute to maintain or even to increase the densities of soil- and wind-borne pests and pathogens. Askew and Struik (2007) summarized that these volunteers create the following detrimental effects:

(i) Disease carry-over to other potato crops

(ii) Pest carry-over in foliage or tubers

(iii) Yield and quality problems in potato or other crops, especially vegetables

(iv) Additional cost

Directly, volunteers competing for resources with other crops decreases crop yield. Furthermore, they can cause direct damage to the harvested products by lowering the product quality, especially in vegetables. Besides resource competition on space, sun, nutrients, air and water the main problems are the indirect effects of volunteers in other crop species that were described in the following. Volunteer plants are carry-over bridges for build-up populations of pests and diseases, or directly spread spores from not potato grown fields into potato fields. Volunteers contribute to uncontrolled persistence and severity of many fungal, bacterial and viral diseases by cutting the cultivation break. Moreover, volunteers are important source of infection with viral diseases, especially non-persistent viral diseases like Y-Virus (Hunnius 1978). These potato plants profusely grow in wheat and corn fields and have been implicated as the chief source of primary inoculum and aphid population supporting massive potato virus epidemics (Thomas and Smith 1983). Furthermore, volunteers facilitate the survival of numerous diseases like phoma, bacterial rot and late blight (Hunnuis 1978). Adolf et al. (2020, pp. 315) claimed that elimination of volunteers reduces the potential of late blight disease. Although often described as soilborne pathogens, survival of bacteria as *Ralstonia solanacesarum* is very short lived at low temperature in bare soil but it is significantly higher in alternative wild host plants (especially overwintering volunteers). Also quarantine pathogens, for example, potato ring rot (*Clavibacter michiganensis* subsp. *sepedonicus)* can overwinter in whole potato tubers and debris (Charkowski et al. 2020, pp. 354). Nilsson (1975) suggested that volunteer plants may also exacerbate the problems of controlling Colorado beetle (*Leptinotarsa decemlineata* Say.).

However, the most precarious threat of volunteers is the proliferation of potato eelworms. Only four volunteer potatoes per square meter increase the number of nematodes from double to triple (Hunnius 1978). In the Netherlands it is prohibited to grow potatoes on one field more than one year in four years, except counteractive measures are initiated. In some region potatoes are grown 50 % in crop rotation (Lumkes 1979). When there are still volunteer plants on not potato cultivated fields in such a crop rotation, problems with potato cyst nematodes *(Globodera spp.)* are inevitable. Quarantine or other regulatory measures are used in many countries to reduce potato cultivation in crop rotation. Banning potatoes in crop rotation is often the economic worst-case scenario for most potato famers. In Germany, tight potato crop rotations lead to a new virulence type of *Globodera pallida* population *Emsland* for which no resistance exists. At least, nematode populations decrease by up to 40.0 % per year when non host crops are grown (Stevenson et al. 2001, pp. 50). Therefore, a forceful managing of volunteer potatoes to maintain cultivation breaks is the best method to prevent most potato pests and diseases.

## 2.2 The role of volunteer potatoes in agriculture

'The origin of the volunteer potato problem is the inability of any existing potato harvester to remove all the tubers from the field', by Rahman (1980). Following, it is demonstrated that the origin of this problem starts with harvesting and become a major problem in potato production. The number of potatoes left on the field is very variable as current literature showed. In early research field leavings of 124 000 up to 370 000 tubers per ha have been reported in Scotland and the U.K., respectively (Perombelon 1975, Lutman 1977). In contrast, Newberry and Thornton (1998) sampled unharvested tubers ranged from 10 361 to 48 594 per ha with an over location mean value of 27 689 tubers. Askew and Struik (2007) summed that up to 500 000 tubers per ha could remain on the field. Recently, an investigation in Germany stated harvest losses between 87 500 to 158 650 potato tuber per ha (Heintges 2017). This approximates to a 12-fold increase over normal planting rate. According to another estimation, up to 10.0 % of the yield of potato tubers is lost during the process of harvesting (Rahman 1980). Since potato tubers are susceptible to frost damages, research on mortality during winter recorded substantial numbers of up to 50 000 spouts per ha survive in winter and subsequent arise in wheat fields (Lumkes 1979; Lutman 1977) Boone and van der Elst (1977) stated that in the Netherlands 80.0 % of all tubers decay in winter. Lumkes (1979) dissented that only 20.0 - 50.0 % of all remaining tubers in spring germinate. Rahman

(1980) summed that the tuber loss represents a potential volunteer population of two to thirty potato plants per square meter.

The amount of field leavings of potato tubers after harvesting depends on processing direction and on the aimed potato size (Heintges 2017, Peters 2018), whereas in the processing direction inseed-, and food-potatoes the most volunteers occurred. Fewer volunteer potatoes were produced on fields with starch potatoes (Heintges 2017). On fields where processing potatoes are grown the amount of remaining potatoes in dt per ha was equal to food-potatoes but the number of tubers per ha was lower (Peters 2018). Peters (2018) also claimed that the number of volunteer potatoes depends on variety. Most volunteer tubers are less than four diameter and their distribution in soil suggest that they had fallen between the bars of the harvester elevators (Lutman 1977). Nearly 30.0 % of all remaining tubers were on soil surface with 39.0 % in the top 5.0 cm and 31.0 % deeper than 5.0 cm (Lutmann 1977). Newberry and Thornton (1998) ascertained a tuber distribution of 19.0 % tubers on soil surface, 20.7 % in the upper layer 0.0 - 5.0 cm and 44.0 % in the deeper layer 5.0 - 20.0 cm and 16.4 in deeper layer than 20.0 cm. Their investigations demonstrated that tuber size ranged from 1.0 g to 406.0 g with an over location mean tuber size of 22.4 g. Lutmann (1977) showed that over 80.0 % of the remaining tubers were between 1.0 and 4.0 cm. Peters (2018) stated that even sized grown potatoes did not fall through bigger distances of sieve chains. Hence, the remaining larger tubers occurred due to an inadequate depth of harvester blade and spillage from harvester and trucks (Boydston et al. 2006). In the same manner new investigations of Peters (2018) showed less potato tuber leavings correlated with harvester blade depth from 16.0 cm to 19.0 cm while driving speed had no impact on field leavings of potatoes.

## 2.3 Strategies to control volunteer potatoes

Since volunteer potatoes have developed into a serious and expensive problem in agriculture, the integrated control of volunteer potatoes is of increasing importance. The first step of integrated control management is the reduction of potato causalities during harvesting. This begins with the selection of the potato field in the year before cultivation. Fields with high soil density or fields with lots of stones hinder harvesting or mislead to choose sieve chains with bigger distances in between to get rid of stones and clods. In the following, the management of potato crop should attempt to achieve an equal sorting, especially fewer small tubers which are the most common source of potato field losses. Also, the shaping of variety is an important factor because lonely oval tubers are more susceptible to fall between the sieve chains than round shaped tubers. Furthermore, blade depth and the distances of the sieve chains of the harvester have a significant impact on the number of remaining volunteer potatoes per ha (Lumkes 1979, Peters 2018). After harvesting tillage has also a significant impact on volunteer potato appearance in next year, whereat investigations favour no special tillage equipment (Lumkes and Beukema 1973, Thomas and Smith 1983, Newberry and Thornton 2004). Lumkes (1979) claimed that the intensive destruction of the remaining potatoes promoted rotting over winter. But it was not explained which tillage equipment should be chosen for this purpose. Moreover, the use of tillage to control volunteers is further described in chapter 2.5.

When all integrated measures fail, conventional operating farmers can use herbicides in the following field crops. However, in most agricultural crops volunteer potatoes cannot be completely controlled by herbicides, because of large carbohydrate reserves in the tuber and the ability to resprout after various control tactics. Herbicides often reduce the weight of new tubers produced by volunteer potatoes but are not as effective in reducing the number of new tubers produced (Boydston 2006). In the following text only, active ingredients were considered when they are components of a product that are accredited in Germany for potato cultivation at this juncture. Cereals are common field crops after potato cultivation, especially wheat (Demmel et al. 2019). In cereal monoculture volunteer potatoes can survive in soil over many years (Perombelon 1975). In this culture herbicides with the active ingredient fluroxypyr were used against volunteers. The efficiency of those herbicides highly depends on different environmental factors and is often limited (Benker 2015). Another option is the late-application of glyphosate in laid grain on parts of the field or after grain harvesting on stubble. For the last one the potato should build up enough leaf material to absorb the active ingredient glyphosate. Hence, Rahman (1980) found that glyphosate not only kills the aerial parts but is translocated to subterranean parts, including the early formed daughter tubers. Thus, the treatment was glyphosate is generally known to be very efficient, because it will kill the daughter tubers (Rahman 1980).

Particularly in sugar beets, the control of volunteers is extremely difficult because of the low competitive strength of the small seedlings. In sugar beets, the LWK NRW (Landwirtschaftskammer North Rhine-Westphalia) recommend mixtures of ethofumesat, pendimethalin, desmedipham, lenacil, triflusulfuron and clopyralid applied two times in a temporal distance of seven days. This application can suppress the volunteers but not fully control and can also cause phytotoxic reactions of the sugar beets (Pfaffenroth et al. 2020, pp. 499). Rahman (1980) summed that also ethofumesat influence potato sprouting, but after some weeks the potato recover. Despite this, the spray application of herbicides in sugar beets is often followed by the manual control volunteer potatoes by the farmer.

The highest efficiency of herbicides against volunteer potatoes is achieved by accredited corn herbicides. Boydston (1996) claimed that spraying of Glyphosate after planting killed emerged potatoes, but new potato shoots emerged within two weeks. Hence, a lot of new research has been done by the LWK NRW and LWK of lower Saxony regarding the spray application with the highest efficiency to defend volunteer potatoes (Pfaffenroth et al. 2020). The herbicide group of triketones seemed to have the best efficiency. Following the LWK NRW recommend a split spray application of mesotrione in a first step followed by a mixture of foramsulfuron, idosulfuron and thiencarbazone (Pfaffenroth et al. 2020, pp. 354). The investigation of Boydston and Williams II (2005) demonstrated that a single application of mesotrione at 0.07 or 0.11 kg per ha applied at the time of tuber initiation controlled potato top growth of 96.0 - 98.0 %. Their investigation revealed that mesotrione reduce the number and weight of new potato tubers in corn field compared to other herbicide (fluroxypyr, dicamba, carfentrazone-ethyl). If volunteer potatoes already formed new daughter tubers at the time of second application the active ingredients clopyralid and picloram should be added. A mixture of the active ingredients clopyralid and picloram hindered the spread of the daughter tubers in following year. But it should be considered that, there was no reduction of eelworms with clopyralid and picloram in the first potato gap year (Pfaffenroth et al. 2020). There is at least one sprouting inhibitor available on the market for field application, viz maleic hydrazide. Maleic hydrazide is used in field application to the green plants approximately two to three weeks after full bloom, then it gets translocated to the tubers (Rahman 1980). Following the content of maleic hydrazide in tubers hinders them sprouting while storage and germinating in field in next year. This treatment is rather expensive and can cause yield losses, as well as the effects lasts only one or two years. Thomas and Smith (1983) claim that maleic hydrazide prevent sprouting excellent in one season and poor in the next. To sum up, there is no chemical treatment known that enable a reliable control of volunteer plants in other crops without a risk of cause damage to these crops (Zaag 1977).

## 2.4 Freezing behaviour of potato

Potato tubers are susceptible to cold injury and therefore low soil temperatures in winter can kill tubers left in soil. This natural aspect of control volunteers by cold is highly discussed in literature (Jones et al. 1919, Wright and Harvey 1921, Wright and Taylor 1921, Wright and Diehl 1927, Lumkes 1974, Boydston et al. 2006). In general, to get freezing injuries in plant tissues, these must be cooled to some degree below the freezing point of water (Jones et al. 1919). Injuries from freezing include membrane disintegration, cell dehydration due to extracellular ice formation, xylem embolism and physical lesions by frost crack. When water freezes within a plant, heat is released during this process which referred as exotherm. The temperature at which an exotherm occurs is referred as ice nucleation temperature within cells, and the stabilization of temperature following an exotherm represents the actual freezing point of the tissue (Boydston et al. 2006). To avoid this exotherm and frost damage plants use cold acclimation. This is a complex process involving modification of membrane lipid composition, increase in compatible solutes, enhancement of antioxidative mechanisms and synthesis of protective proteins (Lee et al. 2012).

Potatoes tubers in view of the fact that that there is no killing tissue are different in susceptibility to frost than other crop species. In potato tubers soluble sugars accumulate via hydrolysis of starch and induce freezing point depression and protect cell structures from freezing-induced dehydration, although the mechanisms have not been clearly elucidated (Lee et al. 2012). In general, carbohydrate levels, particularly sucrose, have been correlated with increasing freezing tolerance of plant tissues. Lee and colleagues (2012) alleged cold hardiness is closely related to total soluble sugar content in shoots of blueberry. In the case of potatoes, Wright and Diehl (1927) consented the higher sugar concentration during storage consistently correlates with a lower freezing point. Therefore, tubers which have been stored at temperatures slightly below the freezing point of water turn sweet owing to the accumulation of sugar produced by the gradual starch conversation (Jones et al. 1919). In practice, the average freezing point of potato is one degree lower when the potatoes are stored at 0.0 °C than when they stored at 10.0 °C (Wright and Diehl 1927). Ultimately, only 30.0 - 40.0 % of the osmotic adjustment in plants is explained by variation in free sugar concentration, suggesting that other compounds than carbohydrates also participated (Guinchard et al. 1997).

Freezing dynamics of potato tubers in air have been reported for a long time. Early research on frost damage of potatoes were inserted because the enormous loss of food potatoes due to frost and freezing every year. The frost which damage these food potatoes occurred before harvesting and while transporting from field to consumers (Wright and Taylor 1921). Therefore, experiments had been conducted to determine the freezing point of potato tubers during storage, where tubers were not in contact with a soil medium. Only since 1970, the experiments on potatoes tubers as weeds had been launched with a few experiments which investigated the biology of potatoes as weeds on field (Lutmann 1977, Lumkes 1979). Boydston (2006) did the first laboratory experiments on freezing behaviour of potatoes exposed to hydrated and dry soil finding the freezing dynamics between tubers and the nucleation sites of soil water associated with soil. The exact temperature of potato tubers mortality due to cold is discussed in literature for a long time. Moreover, literature dispute about different experimental factors that have been included by research groups in their investigations. These factors are the freezing temperature of the variety, rate of temperature dropping, peel injury, the moisture of peel, the freezing status of the surrounding area, jarring while freezing and tuber size. First the freezing temperature can be described by the point temperature the exotherm occur and is followed by the temperature of freezing. It is a known fact that potato tubers must be cooled some degrees below its freezing point before ice crystallization begins, known as point of supercooling or exotherm (Jones et al. 1919, Boydston et al. 2006). Following this exotherm there is a temporary rise of temperature to a higher degree, stabilizing in the true point of freezing (figure 1). At least the kind of freezing injury can be evaluated in different ways. This can be described as frost necrosis characterized by three types, vascular, ring, net and blotch, or only by determining the sprouting percentage after injury.

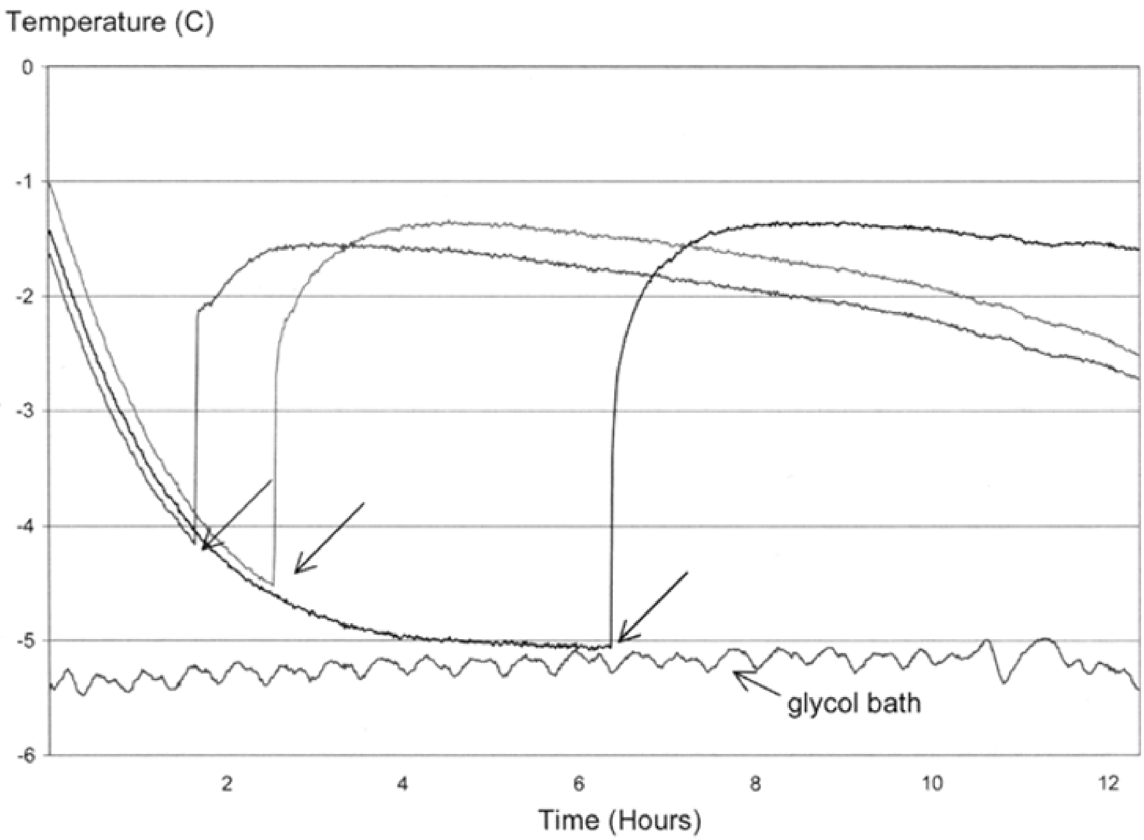


**Figure 1:** Supercooling and exotherm of three potato tubers in air dried soil columns subjected to cold temperatures. Arrows indicate exotherms occurring at 1.6 h, 2.5 h and 6.3 h, characteristic of the variation observed among all tubers tested (after Boydston 2006).

Muller-Thurgau (1880) was one of the first to publish upon frost injury of potatoes and set the ultimate freezing point of potatoes to - 1.0 °C (Boydston 2006). After elaborate investigations in freezing chambers it was concluded that the freezing point was between - 1.0 °C and - 2.2 °C (Jones et al. 1919, Wright and Taylor 1921, Wright and Harvey 1927, Boydston 2006). Most tubers were supercooled to a temperature between - 3.0 and 7.0 °C before an exotherm occurred (Boydston 2006). Jones et al. (1919) asserted the difference between individual tubers in frost susceptibility but claimed that neither size, variety, maturity nor relative turgidity has an impact on freezing behaviour of tubers. In 1921, Wright und Taylor disproved the assumption that moisture has no impact on freezing of tubers. Their investigation showed that supercooled wet potatoes were more injured, although the injury was not serious. In contrast, Boydston (2006) showed that tubers in hydrated soils supercool much less than tubers in dry soil. Another important aspect to be considered is the fact that jarring when potato tubers are undercooled cause potatoes to freeze (Wright and Taylor 1921). Wright and Taylor (1921) undercooled potatoes while dropping them to the floor. Also, the rate of temperature dropping has an impact on temperature of exotherm and on the point of freezing. If tubers are exposed to rapidly dropping temperatures, they freeze at higher temperature than when temperature were slowly diminished (Wright and Taylor 1921, Wright and Diehl 1927). Early research done by Lumkes and Sijtsma (Lumkes 1974) concluded that potato tubers are killed by exposure of 50 accumulated degree frosts below - 2.0 °C (i.e. 25 hours at - 2.0 °C, 12.5 hours at - 4.0 °C). Up to date, this literature is frequently cited and known under farmers to predict the number of volunteers in the next year. Based on results of Boydston (2006) when minimum soil temperatures reach - 2.0 ° C at a tubers depth for brief period tuber mortality occurs. Expecting mortality of tubers was higher than predict by Lumkes and Sijtsma (Lumkes 1974). Smaller tubers would be expected to supercool more extensively than larger tubers due to the lower number of possible nucleation sites, associated with smaller surface area (Boydston et al 2006). However, Jones et al. (1919) found no relationship between tuber size and degree of super cooling in freezing chambers. Also, the cover crop in winter had an impact on survival of volunteers over winter. Carson (1961) showed that the presence of a cover crop in winter increased the survival. The soil underneath a crop experienced fewer extreme temperature than bare ground. Meyer (2015) consented with explaining that sustainable volunteer control is become a bigger problem with greening over winter.

## 2.5 The effect of tillage as control management practice

The serious and expensive problem of volunteer potatoes as weeds has significant increased over years (Meyer 2015). This is due to the significant decrease in the number of soil frost events over the last 15 years, which occurred predominantly in the eastern central German uplands (Kreyling and Henry 2011). The IPCC (Intergovernmental Panel on Climate Change) confirmed in 2019 the general reduction in frost occurrence in winter and spring, and a lengthening of the frost free season (Jia et al. 2019). This leads to a higher survival rate of remaining potatoes in next year. Additionally, the decreasing numbers of accredited pesticides and increasing demand for organic farming moves tillage in the focus of research specially to eliminate weeds as volunteer potatoes. Tillage influences the management of volunteers as it has an impact on the distribution of potato tubers in soil. It is known that potatoes remaining on soil surface are more susceptible to humidity, frost, and animals like birds. Additionally, the chances of freezing during the winter is higher the closer the tubers are to the soil surface (Rahman 1980, Pickny and Scheid 1999, Meyer 2015). But, as mentioned in chapter 1.3, only 20.0 - 30.0 % of the remaining tubers are on soil surface while 70.0 - 80.0 % are buried in a depth of 20.0 cm (Perombelon 1975, Lutmann 1977, Newberry and Thornton 1998). In general, most tubers are on the soil surface or in a depth up to 10.0 cm depth in soil (Lumkes and Beukema 1973).

Ploughing bury the volunteers to a greater depth (Lumkes and Beukema 1973, Perombelon 1975, Lumkes 1979, Thomas and Smith 1983, Pickny and Scheid 1999). The vertical displacement of the potatoes is greater the closer the potatoes were to the soil surface before tillage. The movement of the potatoes with a fixed-tined cultivator was found to be very low in their experiment (Lumkes and Beukema 1973). While common ploughing after harvesting moves potatoes to a greater depth and decreases the chances of freezing an unspecific non-inverting tillage is recommend (Lumkes and Beukema 1973, Perombelon 1975, Lumkes 1979, Pickny and Scheid 1999). Meyer (2015) claim that for sustainable control of volunteers a cultivator with wing shares should be used first than followed by some implements which destroy potatoes. Another factor affecting the efficiency of tillage against the appearance of volunteers is crushing as this limits the growth of volunteer plants in next year. Maximizing the chance of rotting by intensively crushing of remaining potatoes with tillage after harvesting enhance the mortality of tuber in winter (Boone and van der Elst 1977; Lumkes 1979). Boone and van der Elst (1977) also stated that soil structure, especially soil structure heterogeneity in the arable layer, which is clearly altered by tillage, has a significant impact on germination of volunteers in next year. Germination experiments proved that uncrushed tubers do not germinate in dense soil compared to lose soil. Lumkes (1979) explained that remaining tubers in spring respirate more than in winter as potatoes suffocate in dense or highly hydrated soils. It has to be noted that there is a lack in research dealing with the crushing effects of tillage implements on potato tubers.

Frozen tubers are susceptible to jarring which makes frost tillage an effective management tool to the control of volunteer potatoes (Wright and Diehl 1921). The repeated jarring of potatoes makes them more susceptible to further frost. In addition, the method of frost tillage was developed. Frost tillage is defined by waiting with tillage until first frost kill tubers on soil surface and subsequent tillage expose additional tubers to soil surface to freeze (Thomas and Smith 1983). Field experiments showed that ploughing or rototilling after two days of -3.0 °C reduced volunteer potatoes. Bavarian farmers immediately reported this observation on praxis fields. Fall tillage alone by either rototilling or ploughing reduced volunteers about one-third of the level occurring after tillage in the first year of their experiment (Thomas and Smith 1983). However, the operating principle is not clearly discussed in literature. Similar research on tillage was done by Newberry and Thornton (2004) who promoted that tillage after harvest affect the number of volunteer potato plants. The first experiment in 1998 was done with the tillage treatments: Rotary disk, paraplough, mouldboard plough or not tilled. They found no effects of tillage on the appearance of volunteer potatoes. But experiments in 1999 proved that the mouldboard plough led to more volunteer plants than other tillage variants. Experiments done in 2000 showed also that the mouldboard plough produced the highest number of plants and paraplough the lowest (Newberry and Thornton 2004). To sum up, timed tillage combined with a cover crop could be as effective as chemical treatments in reducing volunteers (Thomas and Smith 1983).

## 2.6 Working operation of tillage implements

Some research was done on the effect of tillage on appearance of volunteer potatoes year, but the direct effect of tillage on tubers infirmity or burying was not clearly discussed. Tillage implements are normally described by their effect on struggle and crushing organic matter and a subsequent incorporation. But also weed elimination throughout tillage is a topic of increasing interest. Especially the mouldboard plough is a primary tillage tool often used to provide soil inversion that bury weeds (Ucgul et al. 2017). Following the mouldboard plough bury potatoes deep in soil (Lumkes and Beukema 1973, Perombelon 1975, Lumkes 1979, Thomas and Smith 1983, Pickny and Scheid 1999). To understand how tillage equipment interfere with potatoes during tillage the working operations of the implements are demonstrated, following. In this master thesis the plough is always described first, followed by the cultivator, the disc harrow and the rotovator.

The mouldboard plough normally is a tool or farm implement used for initial cultivation to inverse soil and create the basis for a seedbed (Ugcal et al. 2017). Another purpose of ploughing is to loosen and turn over the upper layer of the soil, bringing fresh nutrients to the surface, while burying weeds and the remains of previous crop pieces, fungal spores allowing them to decay. The mouldboard plough has a complex geometry surface which determines the tillage quality (Ibrahmi et al. 2017). Ucgul and colleagues (2017) found out that increasing speed lead to a significant reduction in the depth of top soil burial while increased tillage depth only lead to a slight increase in top soil burial. In contrast, skimmer increase the amount of top soil buried below 10.0 cm depth.

The cultivator is used as a modern tillage implement for deep subsoiling like the mouldboard plough. In contrast to ploughing it is more burying and not turning. The second operating area of the cultivator is mixing of stubble and plant residues into soil (Esterl and Knittel 1996, pp. 113). The shares of a cultivator are ordered in exact line distance and fixed together on a frame which are equated on one to six crossbars. The more crossbars the merrier light soil pieces like potato tubers were transported to the soil surface. There are different models of these cultivator shares are available. The duckfoot share with long wing sweeps have a big working width with up to 25.0 cm. (Gommel 1967, pp. 133). When considering the effect of the shares of the cultivator on working operation, it has to be mentioned that Galant and Ingale (2017) stated soil inversion increase with the width of the shares. In line with this, the TopAgrar (2010) stated that the share width in concert with the number of tines determines the working intensity of the implement. The duckfoot shares are mostly common for a flat working operation. These shares cut the soil with a low undercut and a low mixing effect (TopAgrar 2010). So, the duckfoot shares demonstrated a good ability in breaking down soil clods in contrast to other tillage impelements (Sarec and Sarec 2015). Sarec and Sarec (2015) stated in contrast to other publications, that the duckfoot shares have a good incorporation performance of plant residues with thinner steel. Another commonly used shares are the wing shares. These wing shares consist of a separate share tip, the wings and a guide plate. The main working area of the wing shares is between 5.0 - 15.0 cm (TopAgrar 2010). A cultivator with these types of shares is a rigid cultivator which is used mostly for shallow ploughing, destruction of weeds and retention of moisture. If the shares were made from thicker material, with a blunter cutting edge vertical up forces were increased (Fielke et al. 1993). But vertical up forces are known to be reduced in wet soil compared to dry soil conditions which demonstrate that the impact of implements is also affected by soil conditions (Fielke et al. 1993). Berntsen and Berre (1993) stated that the aggregate size distribution after tillage is mainly independent of the implement used, and largely determined by the soil state and the soil's ability to store strain-energy before fracture. When considering this statement, it should be noted that the experiments of Berntsen and Berre (1993) used only slightly different cultivating implements. Following, the cultivator on the one hand was described as implement which pick up potatoes to soil surface when the shares are made of big steel and on the other hand the working operation of the cultivator was described to bury plant residues. A tuber destroying effect cannot be assumed with the cultivator.

In contrast to the cultivator, destructive effects were described for the use of a disc harrow with serrated discs. According to the operating principle the disc harrows belongs to ploughing tools. But commonly disc harrows are used as secondary equipment after ploughing to crumble rough-hewn soil into small pieces. The more inclined the angle of the discs in the direction of travel the more intense is the crumbling and mixing effect. Accordingly, a strong inclined disc position can also produce a turning effect of soil. The good mixing effect of disc harrows allow the use to incorporate straw of grain after harvesting while the notched coulter buries plant residues better into soil. Furthermore, if disc blocks are levelled, the discs have a predominantly cutting effect (Esterl and Knittel 1996, pp. 138). The working tools are arched self-trading discs with a diameter between 40.0 cm to 60.0 cm at a thickness of 0.4 cm steel, where the edge can be jagged or smoothed. Smooth discs intensify the mixing effect in soil, because the soil pieces speed up differently depending on their position on disc. The jagged discs act more aggressive and incorporate bigger plant residues as it penetrates the soil easier (Esterl and Knittel 1996, pp. 138).

A further tillage implement with cutting and destructive characteristics is the rotovator with protractors. The rotovator is a secondary tillage equipment and used after ploughing for seedbed preparation. In comparison to passive tools the rotovator has a superior soil mixing and pulverisations capability (Marenya 2009). Further rotary tillers are used for mulching organic matter into the upper soil layers (Steinmetz 1790, pp.133). The rotary tools are protractors which throwing small pieces of soil backward while slowly moving forward. This results in a consistently pulverized and crumbled upper soil layer. The crushing effect depends on driving speed and number of knifes penetrating soil during roller rotation. The density of the rotovator can be calculated by counting the number of impacts of the protractor per square meter. Guards behind rotary increase crushing effect of soil clods because the soil is thrown against (Gommel 1967, pp. 131).

# 3 The aim of the study

Tillage can be a powerful tool to reduce volunteer potatoes in following crop cultures. In this context, the implement characteristics in term of burying and cutting are of particular importance as their impact on the distribution of tubers in soil. The aim of this study was therefore to figure out which tillage equipment significantly reduce occurrence of volunteer potatoes compared to common ploughing. For this purpose, field experiments were conducted at five locations to find out which tillage implement used after harvesting favours tubers to decay. To do so, six different tillage versions were tested and remaining tubers on soil surface were counted directly after harvesting and clustered in coloured and damage groups. In the following spring the volunteer potatoes were counted in each tillage version and the tuber depth in soil was measured. In detail this work aimed on answering the following hypothesis:

1) Tillage after harvesting has a significant impact on depth distribution of tubers in soil:
   a) The plough buries tubers significantly deeper than other tillage implements.
   b) The rotovator places the tubers in shallow level under soil surface, significantly higher than all other tillage implements.
2) Tillage after harvesting has a significant impact on the number of tubers on soil surface:
   a) Ploughing reduces the on soil remaining tubers significantly compared to other tillage variants.
   b) Frequently cultivating lead to a higher number of buried potatoes on soil surface compared to ploughing.
   c) The rotovator lead to a significantly higher number of volunteers on soil surface compared to ploughing.
3) Intensive cutting of volunteer tubers with the rotovator lead to a significantly higher number of destroyed tubers on soil surface compared to ploughing.
4) Tested tillage implements can reduce the number of volunteer potato plants significantly in next year compared to common ploughing:
   a) Frost tillage reduces significantly the occurrence of volunteer potatoes in next year compared to the plough.
   b) The rotovator reduces the occurrence of volunteer potatoes in next year compared to the plough variant.
   c) Frequently cultivating reduces the occurrence of volunteers significantly in next year, compared to common ploughing.

# 4 Materials and methods

## 4.1 Field experiments

To investigate the effect of post harvest tillage on volunteer potatoes, field experiments were done from October 2019 to May 2020. To achieve for good validity the field experiment was conducted five times in four different federal states of Germany. Only fields where no potatoes were grown five to ten years ago were chosen to avoid occurrence of additional volunteer potatoes. Field experiment one (F 1) and field experiment two (F 2) were initiated in Lower Bavaria. The F 1 was carried out in Arnstorf on a silty loam with 70 ground points. The experiment was located on 18th September 2019. The field experiment two (F 2) was carried out in Vilshofen on a loamy clay soil with 45 ground points. This field was influenced over years by the near of river Donau. The F 2 was located on 17th October 2019. Field experiment three (F 3) was carried out in Baden-Württemberg on a loamy sandy gravelly soil. The experiment was located on 21st October 2019. The field experiment four (F 4) were initiated in lower Saxony on a sandy soil with 30 ground points. The experiment was invested on 15th October 2020. The field experiment five (F 5) in North Rhine-Westphalia also was done on a sandy soil with 30 ground points. This experiment was created on 14th October 2020. The previous crop in F1, F2, F 4, and F 5 was silage maize. Only on the F 3 field spring barley was the previous crop. Before the experimental setup, soils of F 2, F 3, F 4 and F 5 were cultivated with a cultivator first and subsequently tilled with a disc harrow. The soil of F 1 was only cultivated one time. All fields were farmed conventionally excepting the F 3 which was done on an organically farmed field.

## 4.2 Experimental design

The same experiment design was used for the five field experiments (figure 2). The tubers were placed on and in the soil at 24 plots, each with a working width of 3.0 to 6.0 m wide and 1.0 m long. The potatoes tuber plot was placed at the beginning of the tillage strip. Each tillage strip was 40.0 m long. A space of 10.0 m was left in front of the potato plot to accelerate the tractor with the tillage implement on defined speed. After crossing the tillage strip the soil tillage implement was excavated when first tractor tires cross the line of 41.0 m. Thereby the tubers which travel with could remain in associated strip. Following speed resumed and the second potato plot was crossed. Each variant was repeated four times. The trial was not completely randomized but randomly arranged.

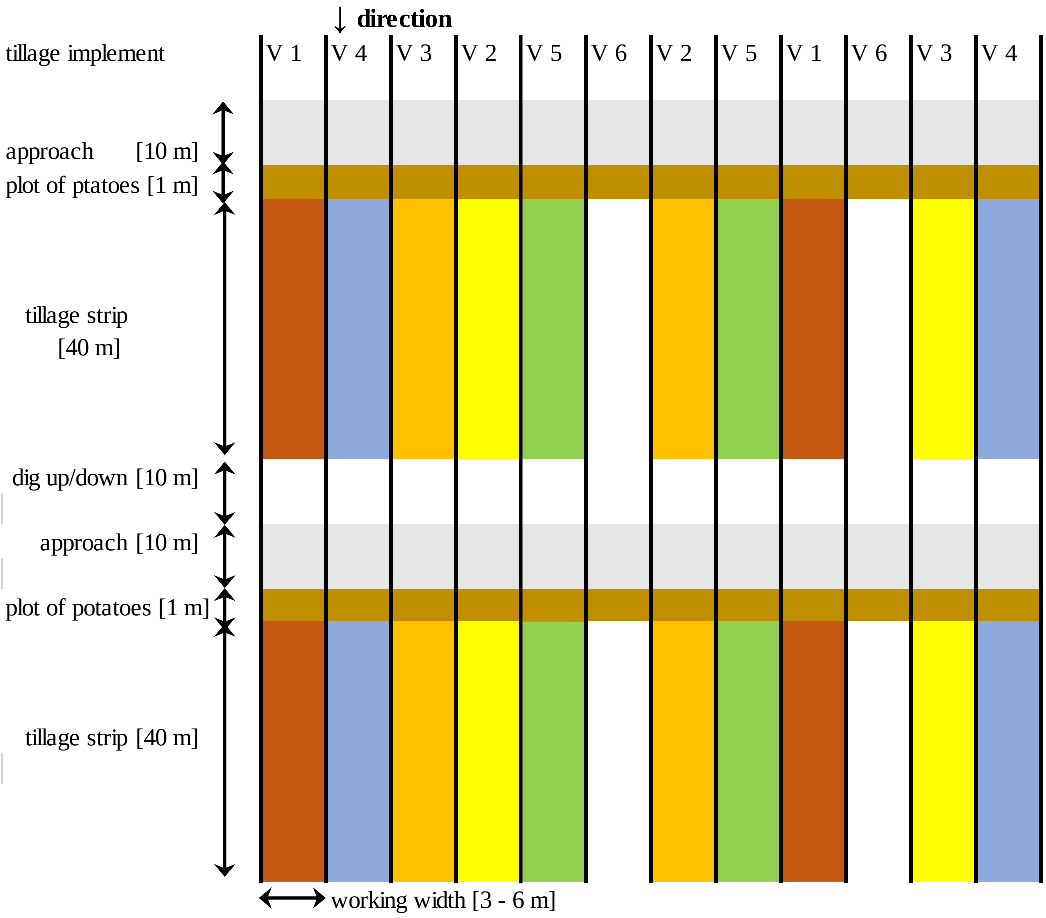


**Figure 2**: Experimental design of the field experiments (F1 - F5). The potato plots are coloured brown and the tillage strips coloured different. V 1 - V 6 are the different tillage variants, repeated four times. V 1= Plough, V 2 = Cultivator 3x, V 3 = Frost cultivating, V 4 = Disc harrow, V 5 = Rotovator, V 6 = No tillage.

The in figure two brown potato plots were set to 1.0 m long and the working width of the experiment bride. The number of potatoes per plot was 40 tubers in all field experiments (F 1 - F 5). 20 of 40 tubers were buried and the other 20 tubers were laid on soil surface of the potato plot (figure 3). The exact allocation of the potatoes tubers is represented in figure 3. The buried potatoes were on same place as potatoes on soil surface. In each plot the distribution of the potatoes was arranged that the same distance was between the potatoes in the strip. To the edges of the plot was right and left 0.25 cm, distance between the plots of 0.5 m to circumvent potatoes rolling in the other plots while tillage.

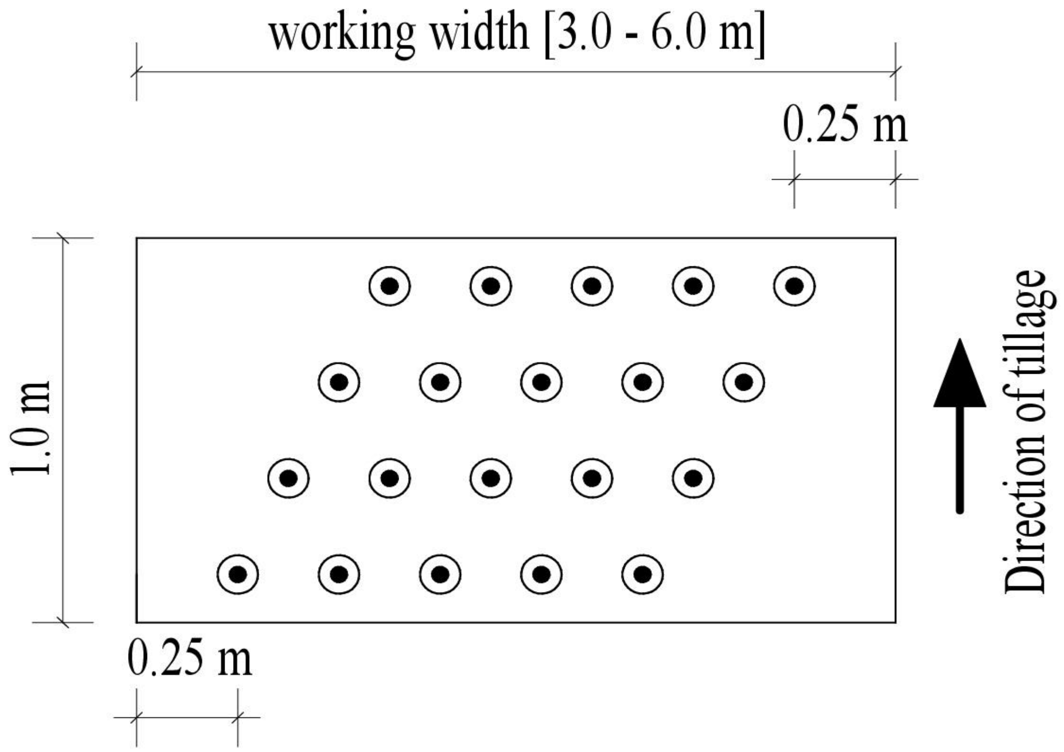


**Figure 3:** Section of the potato plot from the experimental design. Shown is the placement of tubers preceding tillage. Black filled dots demonstrating the tuber at a depth of 10.0 cm and the larger not filled circles represent the tubers on soil surface.

## 4.3 Experimental setup

Representing volunteers, the potato variety 'Bellarosa' from EUROPLANT Pflanzenzucht GmbH (Lüneburg, Germany) was chosen. These seed potatoes were calibrated to a diameter of 2.8 - 3.5 cm to typify small potatoes falling through the sieve chain of the harvester. The seed potatoes were not stored. Representative for the distribution of potatoes after harvesting in soil, potatoes were buried to 10.0 cm in soil. The depth was measured from the underside of the tuber as it was lying in the soil. The other half was located on soil surface. The tubers had been treated with pigment, so that they could be distinguished later. The buried potatoes were coloured pink and the potatoes lying under the soil surface were coloured white. Colouring was done with normal 'Alpine White' wall colour that was mixed with red colour for pink tubers. Previous experiments in 2017 at the Bavarian LFL (bayrische Landesanstalt für Landwirtschaft) showed that the colour has no impact on the fertility and sprouting of the potatoes (Demmel et al. 2019). The colour was mixed 1:1 with water in a bucket. The potatoes were counted until 200 and put into orange potato Raschel bags. These bags with potatoes were dunked in the bucket with colour and dried for two to five days before each experiment was induced. The potato bags were turned around every day to ensure optimal drying.

## 4.4 Experimental soil tillage

To investigate the impact of tillage equipment on appearance of volunteer potatoes, practice-oriented appliances were chosen which is normally available on every farm. In total six variants were investigated in this experiment, which are shown in table 1. In large parts of Germany, the mouldboard plough is normally used after harvesting of potatoes. To represent this standard practice the mouldboard plough was chosen to set the comparative value as variant one (V 1). Furthermore, as reported in literature the cultivator reduces volunteer potatoes by remaining the potatoes after harvesting near the soil surface. Consequently, cultivators with wing crowd shares were chosen if available. The cultivator was used in variant two (V 2) with three crossing times to investigate if frequent running leads to a higher number of potatoes near soil surface. In the third variant (V 3) the cultivator was used two times at different dates. The first crossing was done at the date of the experimental set up in October, temporal equally with the other implements. Second crossing was done in the first frost events, called frost tillage. This means, cultivating when the first centimetre of soil was frozen. On F 1 and F 2 this was done on 5$^{th}$ December 2019. The V 3 of F 3 was frost cultivated on 4$^{th}$ December 2019. In F 4 the V 3 was frost cultivated on 24$^{th}$ January 2020 and F 5 on 2$^{nd}$ January 2020. Like in pre-research done by the LfL (Demmel et al. 2019) the disc harrow with jagged discs was chosen because of the intensive mixing and cutting effect. In variant four (V 4) the disc harrows crossed the tillage strip two times to receive an intense cutting effect. In variant five (V 5) a rotovator with protractors was used crossing one time to achieve a high crushing and cutting effect. In the last variant six (V 6) no tillage, thus no implements were used.

The driving speed and tillage depth was equal in all five experiments (table 1). The plough was driven with 6.5 km $h^{-1}$ and a tillage depth of 25.0 cm. The cultivator with wing crowd shares was driven with 10.0 km $h^{-1}$ and tillage depth of 15.0 cm. The disc harrow was driven with 12.0 km $h^{-1}$ and a tillage depth of 13.0 cm. The rotovator was driven with a speed of 2.0 km $h^{-1}$ and a tillage depth of 14.0 cm. The shaft rotation in F 1, F 3 and F 4 was 1.000 rotations per minute and in F 2 and F 5 540 rotations per minute.

**Table 1:** The tillage variants of the field experiments. Following abbreviations (abbr.) and designations are shown. For each implement the crossing frequency, tillage depth and speed are presented.

| Variants | Tillage type | Implement | Crossing | Tillage depth [cm] | Speed [km/h] |
|---|---|---|---|---|---|
| V 1 | plough | plough | 1 | 23.0 | 6.5 |
| V 2 | cultivator 3x | cultivator | 3 | 15.0 | 10.0 |
| V 3 | frost cultivating | cultivator | 2 | 15.0 | 10.0 |
| V 4 | disc harrow | disc harrow | 2 | 13.0 | 12.0 |
| V 5 | rotovator | rotovator | 1 | 14.0 | 2.0 |
| V 6 | no tillage | no implement | - | - | - |

The tillage equipment was selected on a working width of 3.0 m. Only one field experiment F 3 was done with a working width of 6.0 m and the field experiment F 4 was done with 4.0 m. The farmers used their own tillage equipment, or equipment which was available nearby. The exact description of these implements used in each field experiment is shown in table 2. The description of implement working method and material information is described in the following.

**Table 2:** Denomination of the different soil tillage implements used in the five field experiments (F 1 - F 5).

| Field experiment | Mouldboard plough | Cultivator | Rotovator | Disc harrow |
|---|---|---|---|---|
| F 1 | Lemken EurOpal 5 | Pöttinger synkro 3003 | Celli Ergon 300 | Väderstad carrier |
| F 2 | Lemken VariOpal 8 | Tulp multivator 300 | Celli Tiger 190 | Mandam GAL-C |
| F 3 | Kverneland 2500S - iplough | Horsch cruiser 6XL | Breviglieri maxidouble 630 | Horsch joker 6 CT |
| F 4 | Rabe S-Albatros VHA 140 | Köckerling trio 400 | Kuhn EL 201 | Amazone Catros 3001 |
| F 5 | Pöttinger servo 45+ vario | Lemken smaragd 9 | Krone RS | Lemken rubin 9 |

### 4.4.1 Mouldboard plough

The field experiments were done with different plough types. In F 1 and F 5 a plough with 1.5 m working width was used two times to reach the working width of general 3.0 m. In F

2 a working width of 3.0 m was reached by crossing one time. In creation of trial F 3 the 6.0 m working width were reached with two crossings with each gaged 3.0 m. In lower Saxony in F 4 the working width of 4.0 m was achieved while crossing once. In F 1 the Lemken EurOpal 5 (LEMKEN GmbH & Co. KG, Alpen, Germany) amounted turn mouldboard plough was used with four normal continental bodies and four skim coulters in front of every continental body. The interbody clearance was 100.0 cm by a frame hight dimension of 7.0 x 3.0 cm. The continental bodies were equipped with exchangeable plain shares. In F 2 the Lemken VariOpal 8 (LEMKEN GmbH & Co. KG, Alpen, Germany) with five slatted mouldboards and bar-point shares was used. The interbody clearance was 100.0 cm with continental body frame dimension of 12.0 x 20.0 cm. The Kverneland 2500 isobus (Kverneland Group, Klepp, Norway) semi-mounted turn plough with six universal continental bodies and interchangeable plain shares was used in F 3. This plough was also equipped with six pre skim coulter. The continental body frame dimension was 12.0 x 20.0 cm and the interbody clearance was 100.0 cm. In F 4 the Rabe Super Albatros (Grégoire-Besson GmbH, Bad Essen, Germany) mounted turn plough with five slatted mouldboards and normal spiky tips was used. The continental body frame dimension was 12.0 x 20.0 cm and the interbody clearance was 40.0 cm. The Pöttinger Servo 45 plus (PÖTTINGER Landtechnik GmbH, Grieskirchen, Austria) mounted turn plough with five universal continental bodies and interchangeable plain shares was used in F 5. The plough had five universal skim coulters in front of every continental body. The interbody distance was 102.0 cm. Different to all other ploughs the Pöttinger had two mounted subsoilers.

### 4.4.2 Cultivator (different repetitions)

In the field experiments different cultivator types with wing crowd shares were deployed (table 2). In F 1 the Pöttinger Synkro 3003 (PÖTTINGER Landtechnik GmbH, Grieskirchen, Austria) with three crossbars was inserted. On the frame were 11 fixed shares with chisel point solo wing crowd shares, a narrow space between the shares of 27.0 cm and a line spacing of 10.6 cm. The cultivator was followed by a single steel roller, which included enhanced crumbling effects. In F 2 the Tulip multivator 300 (Peeters Landbouwmachines B.V., Etten-Leur, Netherlands) also with three crossbars and a space between the 10 spring-loaded shares from 27.0 cm was inserted. The shares were followed by a cage roller. In F 3 Horsch criuser 6 XL (HORSCH Maschinen GmbH, Schwandorf, Germany) on a working width of 6.0 m with wider duckfoot spring-tines was used. The cultivator had six crossbeams and a space between the shares of 15.0 cm. The cruiser was known for excellent mixing and distribution of plant residues with its six beams. The cultivator shares were followed by a cage roller. In F 4 the Köckerling trio 400 DSTS (KÖCKERLING GmbH & Co. KG, Verl, Germany) with 4.0 m working width and three crossbeams as well as 13 shares with a distance of 30.0 cm was used. The cultivator shares were followed by cage roller fitted with 54.0 cm diameters. In NRW on F 5 the Lemken smaragd 9 (LEMKEN GmbH & Co. KG, Alpen, Germany) with six shares and a narrow space between the shares of 27.0 cm was used. This cultivator had two crossbeams. The wing crowed shares were followed by a cage roller.

### 4.4.3 Disc harrow with serrated discs

The disc harrows which used in present experiments are shown in table 2. The Väderstad carrier with crosscutter discs (Väderstad AB, Väderstad, Sweden) was subjected because of the cutting effect of the whole field with its different kind of discs. On a working width of 3.0 m the carrier had 24 crosscutter discs with a line distance of 25.0 cm. Each disc had a diameter of 45.0 cm and a cutting square of 16 °. The discs were followed by a single soil runner. The Mandam GAL-C (MANDAM SP. Z O.O., Gliwice, Poland) used in F 2 was a compact disc harrow with 56.0 cm diameter serrated hallow discs. On the frame were 24 discs mounted. The distance between the discs was not mentioned in product description. The discs were followed by 60.0 cm diameter high T-ring roller. The Horsch joker 6 CT (HORSCH Maschinen GmbH, Schwandorf, Germany) compact disc harrow used in F 3 had the serrated discs ordered pairwise for an aggressive cutting effect and a high percolation of soil. The 32 hallow discs had a diameter of 52.0 cm with a line distance of 12.5 cm and a cutting square of 17 ° on working width of 6.0 m. The discs were followed by a roll flex packer. The Amazone Catros 3001 (AMAZONEN-WERKE H. Dreyer GmbH & Co. KG, Hasbergen, Germany) with a working width of 3.0 m had 24 discs with a diameter of 51.0 cm and a line distance of 12.5 cm. The cutting angle of observe discs was 17 ° and in back row 14 °. To get a working width of 2.0 m two discs on each side were remounted to reach the final working width of 4.0 m in F 4. Following, the disc harrow had crossed two time with 2.0 m. The discs are followed by a 3.0 m cage roller. In F 5 the Lemken rubin 9/300 U (LEMKEN GmbH & Co. KG, Alpen, Germany) had 24 hallow discs with a diameter of 64.0 cm and a line distance of 12.5 cm on a working width of 3.0 m. The Lemken rubin 9 had a great cutting angle of 20 ° to the soil, which lead to whole field tillage in case of a tillage depth of 7.0 cm.

### 4.4.4 Rotovator with protractors

The rotovators used in these experiments are shown in table 2. The Celli Tiger 190 and Ergon 300 (CELLI S.p.A., Forli, Italia) rotovators which were used in F 1 and F 2, differed others. The Celli Ergon 300 was a light version for small farms with viticulture or fruits. In contrast, the Tiger version was heavier and for larger farms because the implement can be driven with more speed. Especially, the shape of the bottom of the machine frame differed to other rotovators. This had been revised to facilitate soil flow during operation, while increasing the space between the blades and the bottom of the frame at the same time. This reduced the risk of flooding under wet conditions and also fuel consumption. Both Celli rotovators could enter impulses of 540 to 1.000 shaft speed per minute which lead to a rotor rotation of 318 times per minute of the 72 protractors on a working width of 3.0 m. The tillage depth is between 3.0 cm and 25.0 cm. The protractors have a size of 8.0 x 0.8 cm and six protractors rotating inside. The breviglieri maxi-double 630 (Demtra S.p.A., Molinella, Italia) used in field experiment F 3 rotated 120 blades 258 times per minute with a shaft rotating of 1000 rotations per minute on a working width of 6.0 m. The tillage depth varies between 10.0 cm - 20.0 cm. This rotary tiller was followed by a cage roller. The Kuhn EL 201 Kuhn S.A., Saverne, France) rotary tiller with protractors could also be used with 1.000 shaft rotations per minute which lead to a rotation of 210 - 278 times per minute with 72 protractors on a working width of 3.0 m. This rotary tiller was followed by a maxi-packer roller with scarpers. In F 5 the Krone RS (Maschinenfabrik Bernard Krone GmbH & Co. KG, Spelle, Germany) was used. This rotovator with protractors is up to 35 years old and partly self-constructed. It rotated its 72 protractors 200 times with a shaft rotation of 540 rotations per minute. The Tiller was followed by a self-constructed maxi-packer roller with scarpers.

### 4.4.5 No tillage

The soil of this plots was only tilled before test facility. In F 2, F 3, F 4 and F 5 the soil was cultivated with a cultivator first and subsequently tilled with a disc harrow. The soil of F 1 was only cultivated one time. After burying potatoes in the plots no further tillage was done.

## 4.5 Boniturs

The boniturs on the five field experiments were done in harvest and in spring. In harvest the number, colour and the damage status of the on soil surface remaining tuber was observed. In addition, the depth of the tubers was dug in one repetition in F 5. In spring the number of volunteer plants and the stolon length from tuber to soil surface was observed.

### 4.5.1 Harvest observations

According to experimental setup the harvest observation of remaining potatoes on soil surface was done for each field experiment. An evaluation was done to distinguish between the variants regarding crushing and destroying effects as well as on the potential of the implements to retain the potatoes on soil surface. Destroyed potatoes picked by birds, mice or other animals were not counted as damaged because only the impact of tillage should be investigated in this experiment. Each potato completely remaining on soil surface was count and also each debris of potato was count as one. White and pink tubers were separately counted on soil surface. Damaged white tubers were counted as damaged and also as white tuber, this was done for pink tubers equally. The total number of volunteer tubers on soil surface after tillage was the result of the sum of white and pink tubers on soil surface. The number of white tubers on soil surface was composed by only white tubers, regardless the status of damage. The number of pink tubers on soil surface was the sum of all pink tubers on soil surface, regardless the status of damage. The number of damaged tubers was the sum of counted white and pink damaged tubers. In F 1 the harvest evaluation was done on 30$^{th}$ October 2019. In F 2 the harvest evaluation was done on 18$^{th}$ November 2019. The harvest evaluation of F 3 was done on 5$^{th}$ November. The harvest evaluation of F 4 was done on 12$^{th}$ November 2019. The harvest evaluation of F 5 was done on 4$^{th}$ December 2019. The harvest observation was done in each experiment before second cultivation in V 3 frost tillage. The observation of the distribution of the potatoes in soil was done in one repetition for each variant in F 4 on 5$^{th}$ December 2019. The potato depth was measured from soil surface to tuber bottom edge. A rectangle of 1.0 m x 3.0 m (working width) at the beginning of the potato plot was staked out. The soil was dig over to a depth of 30.0 cm. Tubers were differentiated in pink and white but this was not evaluated further.

### 4.5.2 Spring observations

The spring observation in F 1, F 2, F 3 and F 5 was done by Yvonne Katemann. Only in lower Saxony (F 4) the observation was done by Andreas Meyer because the corona pandemic hindered travelling. In each repetition the volunteer potatoes were dug up. Only in F 1 the potatoes were visually inspected. In F 2, F 3 and F 4 the potatoes were count in total and if the mother tubers were available, they were differentiated in pink and white. Subsequently, the average length from the base of the stolon to the soil surface was measured to draw conclusions about the depth of the tuber in the soil. In F 1 only the total number of volunteer potatoes per plot was counted. The spring observation on F 1 was done on 11$^{th}$ May 2020. Before the spring observation was done in F 1 the farmer applicated glyphosate (Durano TF 5 litre in 200 litre water) on the field because of the high number of dock weeds. This application was done on 28$^{th}$ March 2020 where no potato plant was accumulated. The spring observation on F 2 was done on 27$^{th}$ May 2020. The spring observation on F 3 was done on 25$^{th}$ May. After the last frost event on 10$^{th}$ May, all the potatoes were well visible again on the date of the observation. The evaluation on F 4 was done on 28$^{th}$ May and 2$^{nd}$ of June. In this observation the volunteer potatoes were count visually first and secondly dug up. At the time at second observation not all potatoes could be observed again. Following the highest number of volunteers of each plot was used for the evaluation. The spring observation on F 5 was done on 22$^{nd}$ May. The last frost event of the 11$^{th}$ to 13$^{th}$ May was visible but did not hinder the observation. In Borken the third repetition was damaged by hare. Due to the fact that in Borken only three repetitions available and one is damaged by hare, these results should only be considered as tendencies.

## 4.6 Evaluation of weather data

### 4.6.1 Temperature

The soil temperature at the period of the field experiments was measured by the DWD (German weather service) at different stations from 01$^{st}$ October 2020 to 20$^{th}$ April 2020. To calculate the soil temperature on surface and 10.0 cm depth in soil, the AMBETI/BEKLIMA calculation was used by Tobias Vogt. This calculation used input data of the weather stations nearby the fields of the experiments, such as air temperature, relative humidity, precipitation, wind speed, global radiation and thermal sky radiation. The soil texture was determined according to KA5 (Bodenkundliche Kartieranleitung, 5th edition) to be a loamy sand (Sl3) for the soil temperature calculations.

Calculating the soil temperatures for F 1 and F 2 the data of the DWD station with the name Fürstenzell was used. The stations ID was 5856 and it was located at a longitude of 13.3528 and a latitude of 48.5450, at an elevation of 476.0 m in lower Bavaria. This station was 38 km linear south of the F 2 and 18 km linear distant from the F 1. The temperatures calculated for this station were representative for F 1 and F 2. The soil temperature over winter in Baden-Württemberg was calculated with the data of the DWD station in Villingen-Schwenningen with the ID 5229 at a longitude of 48.045 and a latitude of 8.461 at an elevation of 719.0 m. This station was 24 km linear distant from F 3. The resulting temperature data of this stations were representative for the soil temperatures in F 3. To calculate the temperatures at F 4 the data of the DWD station in Soltau were used. The station had the ID 10235 and was placed at a longitude of 9.793 and latitude of 52.6904 at an elevation of 75.0 m in lower Saxony. The distance between the field experiment and the weather station was 18 km. The results of the data calculation at this station represented the soil temperatures in F 4. The soil temperature of the F 5 was calculated by the measurements of the DWD Station in Borken with the stations ID 617 at a longitude of 51.873 and a latitude of 6.886 at an elevation of 47.0 m. This station was 2 km line distant to the field experiment. The DWD calculated the mean temperature of every hour from 01st October 2020 to 20th April 2020 for the soil surface and the temperature 10.0 cm depth in soil. With these hourly data the mean night temperature was calculated by the mean of the hourly data of 9 pm to 6 am. To calculate the hours of frost below the specific degree < 0.0 °C, < - 1.0 °C, < - 2.0 °C, < - 3.0 °C the hours with the temperate below these degrees were counted and summed over all hours between 01st October 2020 to 20th April 2020.

### 4.6.2 Precipitation

The precipitation at the period of the field experiments was measured by the DWD (German weather service) at the stations described above from 01st October 2020 to 20th April 2020. The DWD calculated the mean hourly precipitation. With these data the weekly precipitation and the total sum over the period of the experiment could be calculated.

## 4.7 Statistics

The statistical analysis was done by using R 3.4.4 packages ‘agricolae’ and ‘foreign’. All parameters were evaluated with an ANOVA to find out differences between the tillage variants. To test for significant differences between the groups the post-hoc test Tuckey-

HSD was run and differences were given in small letters. Different letters after the data indicate significant differences at a probability level of 95.0 % (probability error $\alpha = 5.0$ %) if not stated otherwise. Also the boxplot was done with these packages. The bar charts were created with Microsoft Excel, Version 2005 and the standard deviation was calculated. The standard deviation is illustrated in text with ± followed by the numeric value. Outliers (1.5*IQD) were removed before statistical evaluation of the stolon lengths ($n > 20$). Outliers in the data of the vertical distribution of the tubers in harvest were not removed, because $n \leq 20$.

# 5 Results

The results of the five field experiments were structured and start with the vertical distribution of the tubers in soil. First the results of the harvest observation on the tuber depth in one field experiment in one repetition were stated. Thus, the results of the measured stolon length of the volunteer potato plants in spring were shown to draw further conclusions about the depth distribution of the tubers in soil. In connection, the results of the effect of tillage on the distribution of tubers on soil surface were first demonstrated summarized for the field experiments together (F 1 - F 5). Following, these results of the effect of tillage on the distribution of tubers on soil surface were shown separated for each field experiment (F 1, F 2, …) independently. These results demonstrated the tillage effect on the total number of tubers on soil surface after tillage, the retaining tubers on soil surface, the tubers on soil surface which were buried before tillage and the results of the damage status. These results were described in this mentioned order. Subsequent the results of the effect of tillage on the number of volunteer potato plants in spring are demonstrated. These results were demonstrated summarized for all field experiments (F 1 - F 5) first, and separated for each field experiment independently (F 1, F 2, …) in connection. At least the results of the weather data during the experimental setup were shown for the five field experiments.

## 5.1 Vertical distribution of the volunteer tubers in soil after tillage

The depth distribution of tubers in harvest was evaluated in field experiment four in one repetition. The stolon length in spring was measured in 15 repetitions and provides information about where the tubers laid in the soil. The vertical tuber distribution after tillage is demonstrated in figure 4. The ANOVA analysis showed significant differences in tuber distribution related to the tillage variants. In V 1 the tubers were significantly deeper buried in soil than in all other variants (figure 4). The mean depth in V 1 was 16.7 cm in soil. In V 2 the average depth was 6.2 cm, which was relatively similar to V 3. In V 3 an average tuber depth of 5.6 cm was identified. The average tuber depth of 4.9 cm was determined in V 4. In the V 5 the tubers showed the lowest depth with a mean tuber depth of only 3.4 cm.

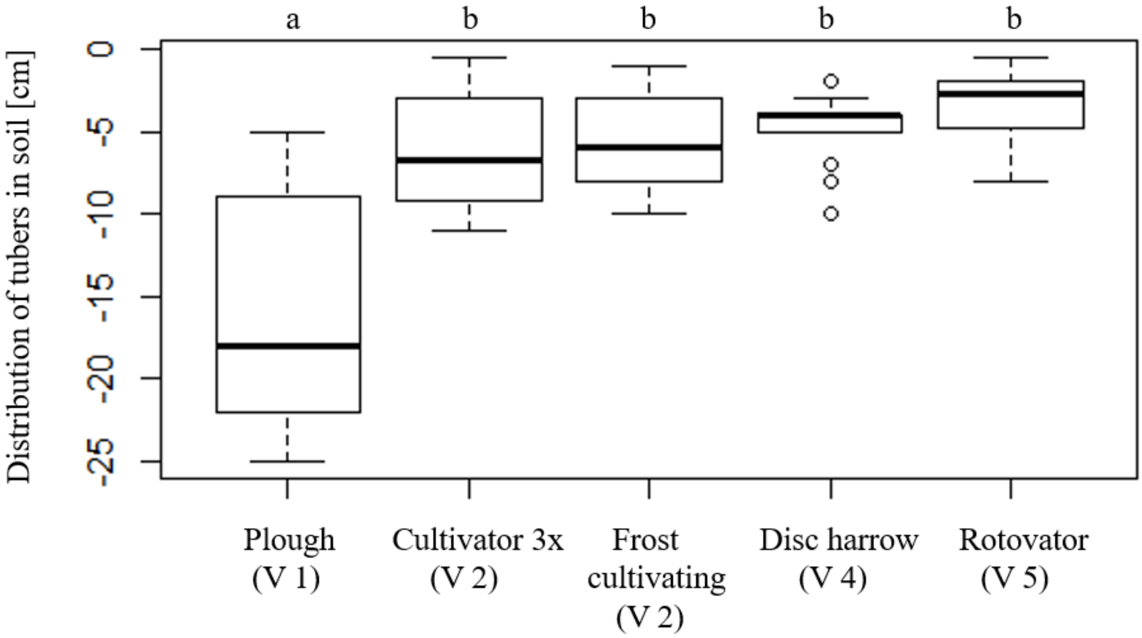


**Figure 4:** Vertical distribution of tubers in soil for different tillage variants (V 1 - V 5, one repetition). Soil depth is gives to the measured length from the tuber bottom edge to soil surface in harvest. Different letters indicate significant differences at a probability level of 95 %.

The results of the spring evaluation of the distribution of the tubers in soil are given in figure 5. The stolons of the tubers found in ploughed variants were significantly longer than the stolons of the tubers in the other variants (V 2 - V 6). No significant difference in the stolon length of the tubers could be evaluated between the cultivator 3x variant, the frost cultivating variant and the no tillage variant. The measured stolon length in the frost cultivating variant differed significant with the plough variant, where the stolons were longer and with the disc harrow and rotovator variants, where the stolons were shorter. The measured stolon length in the disc harrow variant differed significantly with measured length in the ploughed and frost cultivated variants, where the stolons were longer. And the stolon length in the disc harrow variants differed not significantly with the stolon length measured in the cultivator 3x, no tillage and rotovator variants. The stolons in the rotovator variants were significantly shorter than the other tillage variants, except the stolons in the disc harrow variant. The longest stolons in V 1 held an average length of 14.5 cm. In descending order, the variant frost cultivating showed an average stolon length of 9.1 cm, the cultivator 3x variant an average of 8.8 cm, the no tillage variant an average of 8.4 cm, the disc harrow an average of 7.5 cm. The stolons in the rotovator variants showed the shortest average length of 6.7 cm.

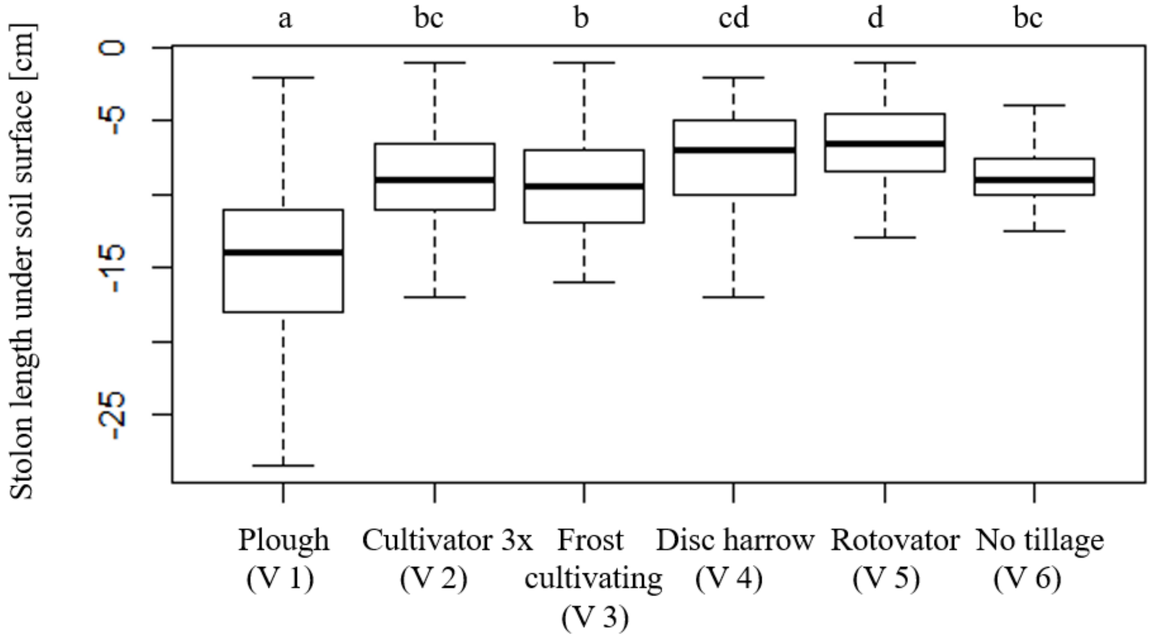


**Figure 5:** Negative stolon length of the potato plants in spring for different tillage variants from attachment of the stolon on tuber to soil surface (denoted as 0.0 cm). Data were averaged over the four experiments F 2 - F 5. Different letters indicate significant differences at a probability level of 95 %.

The length of the stolons were also evaluated separately for every field experiment F 2 - F 5. These results are shown in table 3. In all tested field experiments the significant longest stolons were measured in the plough variant. In F 3 and F 4 the stolon length of the tubers in the other tillage variants did not differ significantly to each other. In both experiments, the shortest stolon length was found on average in the rotovator variants (V 5) in both experiments. In F 2 the second longest average stolon length was measured in the V 2 followed by the V 3 and V 4 and V 6. The shortest stolon length of the tubers in F 2 was measured in V 5. This variant differed significantly with V 1, V 2 and V 3. In F 5 the second longest stolon length were measured in V 3, in descending order followed by the V 6, V 4 and the V 2. The significantly shortest stolon lengths were measured on the tubers in the V 5 of F 5.

**Table 3:** The separted results of the stolon lenght from attachment on the tuber to soil surface for the field experiments (F 2, F 3, F 4, F 5). Different letters indicate significant differences at a probability level of 95 %.

| **Implement** | **F 2** | | **F 3** | | **F 4** | | **F 5** | |
|---|---|---|---|---|---|---|---|---|
| Plough (V 1) | 14.4 ± 5.4 | a | 16.5 ± 6.2 | a | 12.6 ± 5.3 | a | 14.8 ± 4.8 | a |
| Cultivator 3x (V 2) | 9.9 ± 3.0 | b | 6.5 ± 2.8 | b | 8.8 ± 3.8 | b | 8.8 ± 3.4 | bc |
| Frost cultivating (V 3) | 9.5 ±3.0 | b | 6.3 ± 2.9 | b | 8.9 ± 4.8 | b | 9.3 ± 3.8 | b |
| Disc harrow (V 4) | 8.2 ± 3.3 | bc | 6.9 ± 2.4 | b | 6.6 ± 3.0 | b | 8.0 ±3.3 | bc |
| Rotovator (V 5) | 7.4 ± 2.8 | c | 5.6 ± 2.4 | b | 6.7 ± 2.8 | b | 6.4 ± 2.8 | c |
| No tillage (V 6) | 8.1 ± 1.8 | bc | 7.9 ± 1.7 | b | 9.0 ± 1.5 | b | 11.1 ± 1.8 | b |

## 5.2 The effect of tillage on the number and damage status of volunteer tubers on soil surface

The results of the field experiments were evaluated summarized ($n$ = 20) with the data of all experiments together and separated with the data of each experiment individually ($n$ =4). First the summarized results of the five field experiments are shown followed by the separated results for each field experiment.

### 5.2.1 Summarized evaluation of all field experiments

The effect of harvest tillage on the on soil remaining tubers and their damage status was evaluated over all five experiments and is presented in table 4. The data are presented as mean values with corresponding standard deviation. The data of all experiments ($n$ = 20) show that the plough reduced the number of remaining tubers on soil significantly. An average of 1.8 tubers per plough tillage strip with a standard deviation of ± 3.0 was evaluated. The most on surface remaining tubers were observed in V 6 with no tillage, with an average of 20.0 tubers (± 0). In descending order followed by the rotovator with an average of 8.5 tubers (± 5.8). The average of on soil surface remaining potatoes in V 3 was 8.1 tubers (± 3.3). V 2 showed an average of 7.6 tubers laid on surface with a standard deviation of ± 3.8 tubers. An average of 7.3 tubers per tillage strip were observed in V 4, with a standard deviation of ± 3.4 tubers.

**Table 4:** Results of the number of volunteer tubers on soil surface after tillage for the tested implements summarized for all field experiments (*n* = 20). The 20.0 white tubers laid on soil surface before tillage and the 20.0 pink were buried in a depth of 10.0 cm. Different letters indicate significant differences at a probability level of 95 %.

| Implement | Total | | White | | Pink | | Damaged | |
|---|---|---|---|---|---|---|---|---|
| | Number of tubers | | | | | | | |
| Plough (V 1) | 1.8 ± 3.0 | c | 0.3 ± 0.7 | c | 1.5 ± 1.7 | bc | 0.1 ± 0.2 | b |
| Cultivator 3x (V 2) | 7.6 ± 3.8 | b | 5.0 ± 2.8 | b | 2.7 ± 1.9 | b | 0.6 ± 0.7 | b |
| Frost cultivating (V 3) | 8.1 ± 3.1 | b | 6.7 ± 3.3 | b | 1.4 ± 0.9 | bc | 0.3 ± 0.6 | b |
| Disc harrow (V 4) | 7.3 ± 3.4 | b | 5.6 ± 3.2 | b | 1.7 ± 1.6 | bc | 2.2 ± 1.5 | b |
| Rotovator (V 5) | 8.5 ± 5.8 | b | 4.5 ± 27 | b | 4.9 ± 3.8 | a | 5.2 ± 0.2 | a |
| No tillage (V 6) | 20.0 ± 0.0 | a | 20.0 ± 0.0 | a | 0.0 ± 0.0 | c | 0.0 ± 0.0 | b |

The evaluation of the white tubers on soil surface over all experiments showed that significantly highest number of white potatoes was found in V 6, compared to common ploughing. Between all other tillage implements, no significant impact was detected on the number of white tubers on soil surface after tillage over all experiments, excepting using the plough. The plough reduced the on soil remaining white tubers significantly, with an average of 0.3 tubers per tillage strip and a standard deviation of ± 0.7 tubers. In V 3 (frost cultivating) an average of 6.7 (± 3.3) white tubers on the soil surface of the tillage strip were determined. The V 2 (cultivator 3x) showed over all experiments an average of 5.0 tubers (± 2.8) and in V 4 (disc harrow) an average of 5.6 tubers (± 3.2) was ascertained. In V 5 (rotovator) an average of 4.5 tubers (± 2.7) was found. The significantly most pink tubers on soil surface were found in V 5 (rotovator) with an average of 4.9 tubers (± 3.8) located on these tillage strip of all five experiments. In V 2 (cultivating 3x) an average of 2.7 (± 1.9) pink tubers were recorded. The variant with the disc harrow presented an average of 1.7 tubers (± 1.6), followed by V 3 with an average of 1.4 tubers (± 0.9). V 1 showed an average of 1.5 (± 1.7) pink tubers on soil surface. In descending order followed by 0.0 pink tubers in the V 6 (no till). The observations of the cutting status of the tubers after tillage showed significantly most destroyed tubers in V 5 (rotovator) with an average of 5.4 tuber debris found on the soil surface over all five experiments. The V 4 (disc harrow) showed an average of 2.3 destroyed tubers on soil surface, followed by V 2 with 0.6 destroyed tubers per tillage strip, V 3 with 0.3 destroyed tubers per tillage strip, V 1 with 0.1 destroyed tubers per tillage strip and V 6 with no destroyed tuber in tillage strip summarized over all five field experiments.

### 5.2.2 Separated evaluation of the field experiments

The separated evaluation of each field experiment (*n* = 4) showed also significant effects of the tested tillage implements on potato tubers remaining on soil surface (table 5). In table 5 the differences between the means of each field experiment for one tillage variant are shown horizontally. The differences between the means of tillage variants are revealed vertically.

**Table 5:** Separated results of the soil surface remaining volunteer tubers for different tillage variants (V 1 - V 6) for each experiment (*n* = 4). Clustered in total numbers (A), white (B) and pink (C) and damaged (D). Different letters indicate significant differences at a probability level of 95 %.

| **Implement** | **F1** | | **F2** | | **F3** | | **F4** | | **F5** | |
|---|---|---|---|---|---|---|---|---|---|---|
| A | **Total number of tubers on soil surface** | | | | | | | | | |
| Plough (V 1) | 2.0 | c | 2.5 | b | 0.0 | d | 3.5 | b | 0.8 | d |
| Cultivator 3x (V 2) | 9.8 | b | 6.0 | b | 12.0 | bc | 5.5 | b | 4.8 | bc |
| Frost cultivating (V 3) | 7.0 | bc | 6.5 | b | 13.0 | b | 7.0 | b | 7.0 | b |
| Disc harrow (V 4) | 11.5 | b | 7.8 | b | 6.3 | cd | 7.0 | b | 4.0 | c |
| Rotovator (V 5) | 10.3 | b | 17.8 | a | 9.3 | bc | 5.5 | b | 4.0 | c |
| No tillage (V 6) | 20.0 | a | 20.0 | a | 20.0 | a | 20.0 | a | 20.0 | a |
| B | **White tubers on soil surface** | | | | | | | | | |
| Plough (V 1) | 0.5 | d | 0.0 | d | 0.0 | c | 0.8 | c | 0.3 | d |
| Cultivator 3x (V 2) | 4.8 | cd | 4.0 | c | 9.0 | b | 3.8 | bc | 3.3 | bc |
| Frost cultivating (V 3) | 5.5 | bc | 5.3 | bc | 12.0 | b | 5.3 | b | 5.5 | b |
| Disc harrow (V 4) | 10.3 | b | 5.8 | bc | 4.3 | c | 5.5 | b | 2.3 | cd |
| Rotovator (V 5) | 6.0 | bc | 7.8 | bc | 4.0 | c | 2.8 | bc | 2.0 | cd |
| No tillage (V 6) | 20.0 | a | 20.0 | a | 20.0 | a | 20.0 | a | 20.0 | a |
| C | **Pink tubers on soil surface** | | | | | | | | | |
| Plough (V 1) | 1.5 | ab | 2.5 | b | 0.0 | b | 2.8 | a | 0.5 | a |
| Cultivator 3x (V 2) | 5.0 | a | 2.0 | b | 3.0 | ab | 1.8 | a | 1.5 | a |
| Frost cultivating (V 3) | 1.5 | ab | 1.3 | b | 1.0 | b | 1.8 | a | 1.5 | a |
| Disc harrow (V 4) | 1.3 | ab | 2.0 | b | 2.0 | b | 1.5 | a | 1.8 | a |
| Rotovator (V 5) | 4.3 | a | 10.0 | a | 5.3 | a | 2.8 | a | 2.0 | a |
| No tillage (V 6) | 0.0 | b | 0.0 | b | 0.0 | b | 0.0 | a | 0.0 | a |
| D | **Damaged tubers on soil surface** | | | | | | | | | |
| Plough (V 1) | 0.3 | a | 0.0 | b | 0.0 | a | 0.0 | b | 0.0 | a |
| Cultivator 3x (V 2) | 0.3 | a | 0.8 | b | 1.0 | a | 0.0 | b | 0.8 | a |
| Frost cultivating (V 3) | 0.5 | a | 0.8 | b | 0.0 | a | 0.0 | b | 0.0 | a |
| Disc harrow (V 4) | 3.8 | a | 3.0 | b | 1.8 | a | 1.5 | ab | 1.0 | a |
| Rotovator (V 5) | 4.0 | a | 15.5 | a | 3.8 | a | 2.3 | a | 0.8 | a |
| No tillage (V 6) | 0.0 | a | 0.0 | b | 0.0 | a | 0.0 | b | 0.0 | a |

The evaluation of the field experiment in Arnstorf is shown in figure 6. The mean values of tubers are clustered in total, white, pink and damaged tubers on soil surface with standard deviation values included. In Arnstorf the total number of tubers on soil surface differed significantly with the tillage variants (V 1 - V 6) (table 5, section A). Significantly more tuber lied in V 6 on soil surface with a mean of 20.0 tubers. Between the variants V 2 - V 5 no significant difference could be detected, but all variants differed significantly with V 1, except V 2. V 1 showed significantly fewer volunteer tubers on soil surface with a mean of 2.0 tubers in Arnstorf. The V 3 (frost cultivating) presented a mean of 7.0 tubers on soil surface followed by the V 2 (cultivating 3x) with a mean of 9.8 tubers on soil surface. The V 5 (rotovator) presents a mean of 10.3 tubers, this was less than in V 4 (disc harrow) with a mean of 11.5 tubers on soil surface in Arnstorf. Also, the on soil remaining white tubers after tillage differed significantly between the tillage variants in Arnstorf. In V 6 remained 20.0 white tubers on soil surface. Statistically significant lower number remained in V 4 with an average of 10.3 white tubers on soil surface. In Arnstorf the number of white tubers on soil surface in V 4 differed not statistically significant with V 3 and V 5. In V 3 were an average of 5.5 white tubers evaluated and in V 5 6.0 white tubers. Significant fewer white tubers are found in V 2 with 4.8 and V 1 with 0.5 white tubers on soil surface. Also, the on soil remaining pink tubers after tillage differed significantly between tillage variants in Arnstorf. While no pink tuber was found in V 6, a high number of 5.0 pink tubers on soil surface was evaluated in V 2 and 4.3 tubers in V 5. Not significant to V 2 and V 5 but significantly more pink tubers than in V6 were located in V 1 with 1.5 pink tubers, equal with V 3 1.5 tubers, and followed by V 4 with 1.3 pink tubers on soil surface. The evaluation of the damaged potatoes by tillage showed no significant difference between the variants in Arnstorf (table 5, section D). The V 1 and V 2 both had a mean of 0.3 destroyed tubers on soil surface, followed by the V 3 with 0.5 tubers. A higher mean damaged value of 3.8 tubers in V 4 and 4.0 tubers in V 5 could be determined, with no statistically significance. In V 6 was no damaged potato tuber detected.

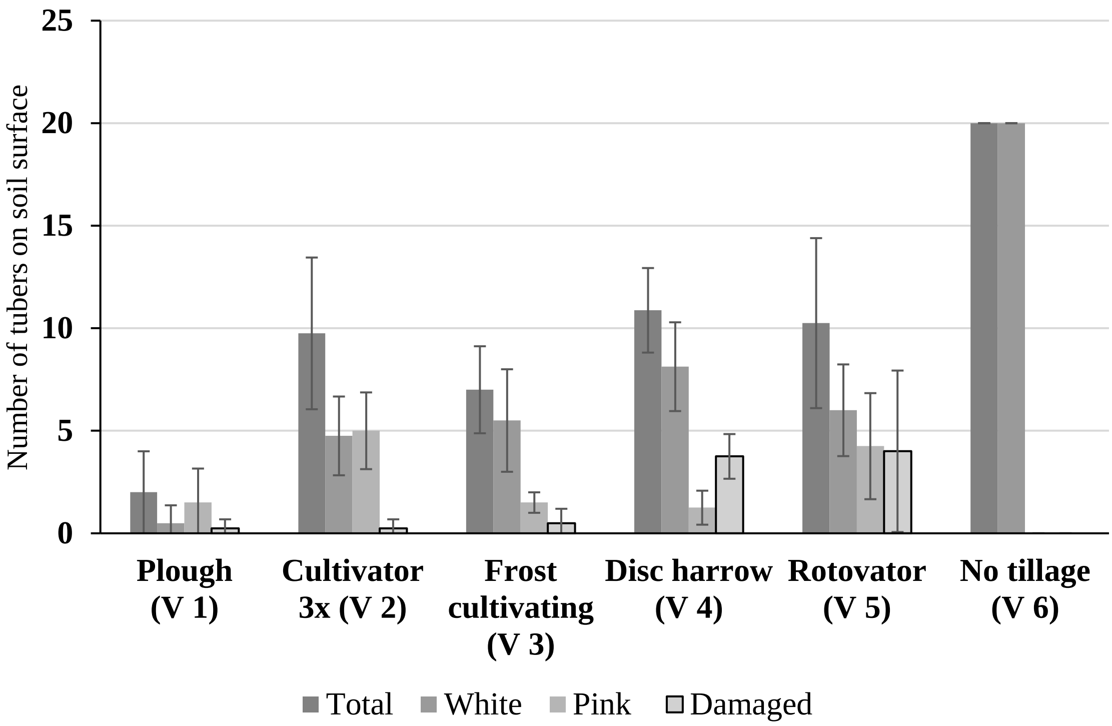


**Figure 6:** Number of tubers on soil surface after tillage for the different tillage variants (V 1 - V 6) in field experiment one (F 1). Presented are the mean number of totals, white (on soil surface before tillage), pink (buried before tillage) and damaged tubers in every tillage variant with standard deviation.

The F 2 in Vilshofen (Bavaria) showed a significant effect of post harvesting tillage on soil surface remaining volunteer potatoes (table 5, figure 7). The evaluation of the total tubers demonstrated that in V 6 and V 5 significantly most potatoes remained on soil surface (table 5, section A). In V 6 remained an average of 20.0 tubers on soil surface and in V 5 an average of 17.8 tubers. A horizontal comparison of the total number of on soil remaining potatoes in the V 5 pointed out that over all five experiments in F 2 were on average most tubers on soil surface. Further, in F 2 no significant difference of tillage on the on soil remaining tubers between the variants V 1 - V 4 was determined. Detected was in V 1 an average of 2.5 tubers, in V 2 6.0 tubers, in V 3 an average of 6.5 tubers and in V 4 an average of 7.8 tubers on soil surface. The comparison of the white tubers on soil surface in Vilshofen exhibited the significant difference of V 1 with zero white tubers on soil surface and V 2 with 4.0 white tubers on surface. Also, the variants V 3 - V 5 differed significantly with V 1. In between V 3 - V 5 no significant difference could be detected. In V 3 were 5.3 white tubers, in V 4 were 5.8 white tubers and in V 5 were 7.8 white tubers ascertained. Analysing pink tubers on soil surface showed that the V 5 significantly differed from all other variants in Vilshofen. In V 5 an average of 10.0 pink tubers were found on soil surface. In descending order in V 1 were an average of 2.5 tubers, in V 2 and V 4 an average of 2.0 tubers, in V 3 an average of 1.3

tubers and in V 6 no pink tuber evaluated. The evaluation of the damaged potatoes on soil surface in Vilshofen pointed also a significant most destroyed tubers in the V 5 out compared to all other variants. While in V 5 an average of 15.5 damaged tubers were sought, in other variants highest number of damaged potatoes were in V 4 identified with 3.0 tubers. In V 2 and V 3 0.8 damaged tubers were determined followed by V 1 and V 6 with no damaged tuber on soil surface.

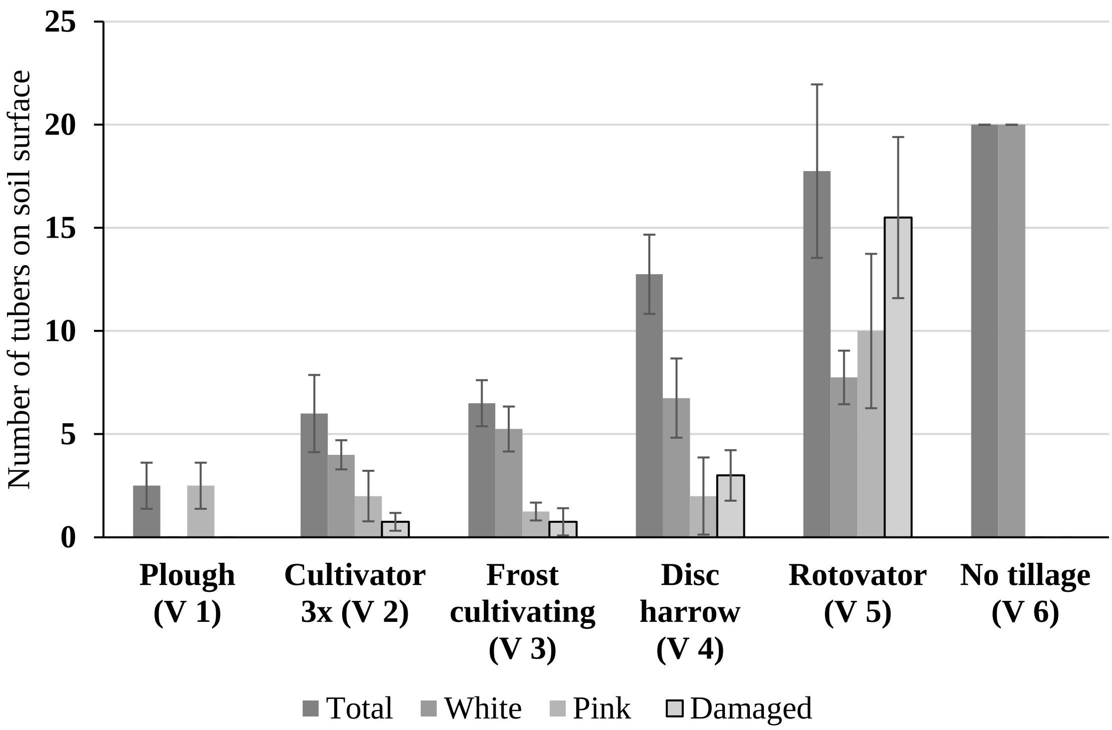


**Figure 7:** Number of tubers on soil surface after tillage for different tillage variants (V 1 - V 6) in field experiment two (F 2). Presented are the mean number of totals, white (on soil surface before tillage), pink (buried before tillage) and damaged tubers in every tillage variant with standard deviation.

The results of the evaluation of the field experiment in Baden-Württemberg with level of significance and the total comparison to other experiments is shown in table 5. The average tubers clustered in total, white, pink and damaged tubers with standard deviation is shown in figure 8. In Baden-Württemberg the number of total tubers on soil surface after tillage significantly differed between the tillage variants (table 5, section A). The V 6 showed most tubers on soil surface, with an average of 20.0 tubers. In descending order followed by V 3 with an average of 13.0 total tubers on soil surface. V 3 differed significantly with V 6, V 4 and V 1 and but not with V 2 and V 5. In descending order, V 2 showed an average of 12.0 tubers and in V 5 an average of 9.3 total tubers on soil surface were found. Both did not differ significantly with each other. The V 4 indicated an average of 6.3 total tubers and differed significantly with V 3 and V 6, but not with other V 1, V 2 and V 5. In V 1 in Baden-Württemberg no tuber was found. V 1 differed significantly from all variants, except V 4. The number of white tubers on soil surface demonstrated a significant difference between the tillage variants in Baden-Württemberg also (table 5, section B). While most tubers were found in V 6 with an average of 20.0 tubers, fewest were found in V 1 (zero tubers). Significantly fewer compared to V 6, were evaluated in V 3 with 12.0 tubers and in V 2 with 9.0 white tubers on soil surface. Also, significantly fewer tubers were located in V 5 with 4.0 and in V 4 with 4.3 tubers, compared to the variants named in sentence before. The analysis of the pink tubers on soil surface showed also significant differences between tillage variants in Baden-Württemberg (table 5, section C). On average most pink tubers were located in V 5 on surface (5.3 tubers). This result differed significantly with V 1, V 3, V 4 and V 6. No significant difference could be identified to V 2 with an average of 3.0 tubers. The variants in descending order revealed an average of 2.0 tubers in V 4, an average of 1.0 tuber in V 3 and an average of 1.0 in V 1 and V 6. The analysis of damaged tubers on soil surface after harvest tillage revealed no significant difference between the tillage variants in Baden-Württemberg (table 5 section D). Variants 1, 3 and 6 showed an average of no damaged tuber on soil surface. The V 2 demonstrated an average of 1.0 tuber, in ascending order followed by V 4 with 1.8 damaged tubers and 3.8 damaged tubers in V 5.

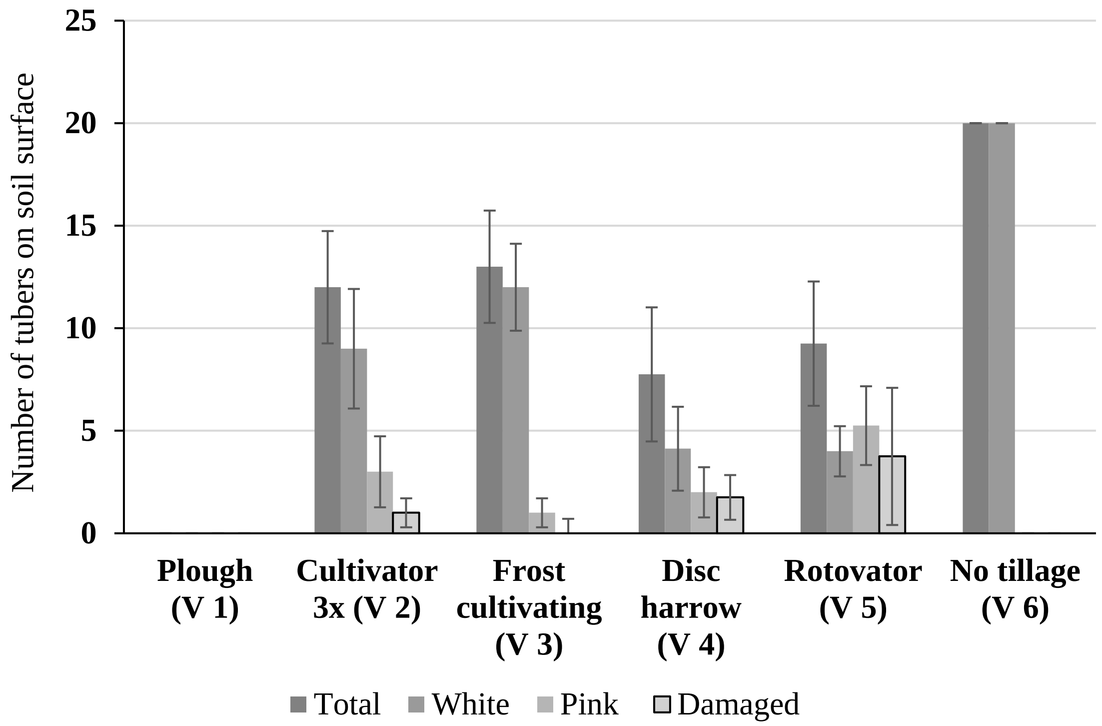


**Figure 8*:*** Number of tubers on soil surface after tillage for different tillage variants (V 1 - V 6) in field experiment three (F 3). Presented are the mean number of totals, white (on soil surface before tillage), pink (buried before tillage) and damaged tubers in every tillage variant with standard deviation.

The results of the evaluation of the field experiment in lower Saxony with level of significance and the comparison to other experiments is shown in table 5. The average tubers clustered in total, white, pink and damaged tubers with the standard deviation values are presented in figure 9. This field experiment demonstrated also significant differences of on soil remaining tubers between the tillage variants. Investigating the total number of tubers on soil surface showed that V 6 featured significantly most tubers with an average of 20.0 tubers. All other tillage variants did not differ significantly to each other, regarding total number of tubers on soil surface. While V 3 and V 4 with an average of 7.0 presented second most tubers, V 2 and V 5 showed with an average of 5.5 fewer tubers. The fewest potato tubers were fund in V 1 with 3.5 total tubers on soil surface. The analysis of the white tubers demonstrated significant differences between the tillage variants in lower Saxony. In V 6 the most tubers were found, with an average of 20.0 tubers. The V 4 showed an average of 5.5 tubers on soil surface followed by the V 3 with an average of 5.3 tubers on soil surface, in descending order. V 2 and V 5 differed significantly to V 6 but not to V 1. V 2 presented an average of 3.8 total tubers and V 5 an average of 2.8 tubers. In V 1 an average of 0.8 tuber could be analysed. The investigation of pink tubers on soil surface showed no significant difference on field experiment in lower Saxony. In descending order, V 5 and V 6 showed average most pink tubers on surface with an average of 2.8 tubers followed by an average of 1.8 tubers in V 3 and V 2. V 4 presented 1.5 pink tubers and in V 6 no pink tuber on soil surface was evaluated. Investigation of the number of damaged tubers on soil surface after tillage showed significant differences between the tillage variants. The V 5 presented significantly most damaged tubers on soil surface with an average of 2.3 tubers compared to all other variants, except V 4. V 4 differed not significantly to all variants with an average of 1.5 damaged tubers on soil surface. Variant 1, 2, 3 and 6 showed no damaged tuber on soil surface.

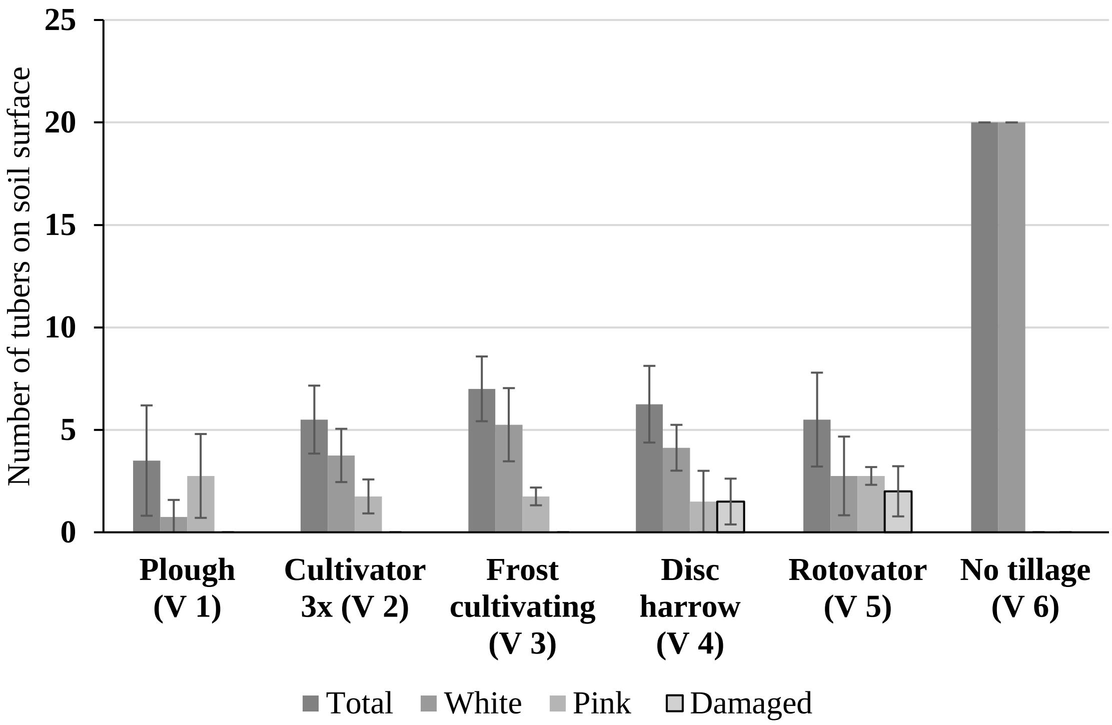


**Figure 9:** Number of tubers on soil surface after tillage for different tillage variants (V 1 - V 6) in field experiment four (F 4). Presented are the mean number of totals, white (on soil surface before tillage), pink (buried before tillage) and damaged tubers in every tillage variant with standard deviation.

The results of the evaluation of field experiment in NRW with level of significance and the comparison to other experiments is shown in table 5. The average tubers clustered in total, white, pink and damaged tubers with the standard deviation value are shown in figure 10. Also, in F 5 significant differences in the number of total and white volunteer tubers on soil surface were found. The average number of damaged potatoes and the number of pink tubers on soil surface differed not significantly between the tillage variants in NRW.

The investigation of the total number of tubers on soil surface showed most tubers in V 6 with 20.0 tubers. The V 6 differed significantly to all other variants. Significantly fewer tubers were investigated in V 3 with an average of 7.0 total tubers and in V 2 with 4.8 total tubers on soil surface. V 3 differed significantly to V 4 and V 5 with an average of 4.0 total tubers on soil surface. V 2 differed not significant to V 4 and V 5. Significantly fewest number of tubers were presented in V 1 with an average of 0.8 tuber. V 1 differed significantly to all other tillage variants in total number of tubers on soil surface. White tubers were found most in V 6 with an average of 20.0 tubers, significantly different to all other variants. In descending order, followed by the V 3 with 5.5 white tubers on soil surface. V 2 stated an average of 3.3 white tubers, whereat the difference is not statistically significant to V 3. Both, V 3 and V 2, differed significantly to V 4 with an average of 2.3 tubers, V 5 with an average of 2.0 tubers and V 1 with 0.3 white tuber. V 1 differed not significantly with V 5 and V 4 in number of white tubers on soil surface but significantly with V 2, V 3 and V 6. In NRW no significant tillage effect on number of pink potatoes on soil surface could be found. The highest number of pink tubers on soil surface was found in the V 5. In V 5 an average of 2.0 pink tubers were counted, followed by the number of V 4 with an average of 1.8 tubers. V 3 and V 2 presented both 1.5 pink tubers and V 1 0.5 tuber, followed by V 6 with no pink tuber on soil surface. The evaluation of the damaged tubers on soil surface in NRW demonstrated also no significant differences between the tillage variants. Most damaged tubers were found in V 4 with an average of 1.0 tuber followed by the V 5 and V 2 with an average of 0.8 tubers. In V 1, V 3 and V 6 no damaged tubers were found.

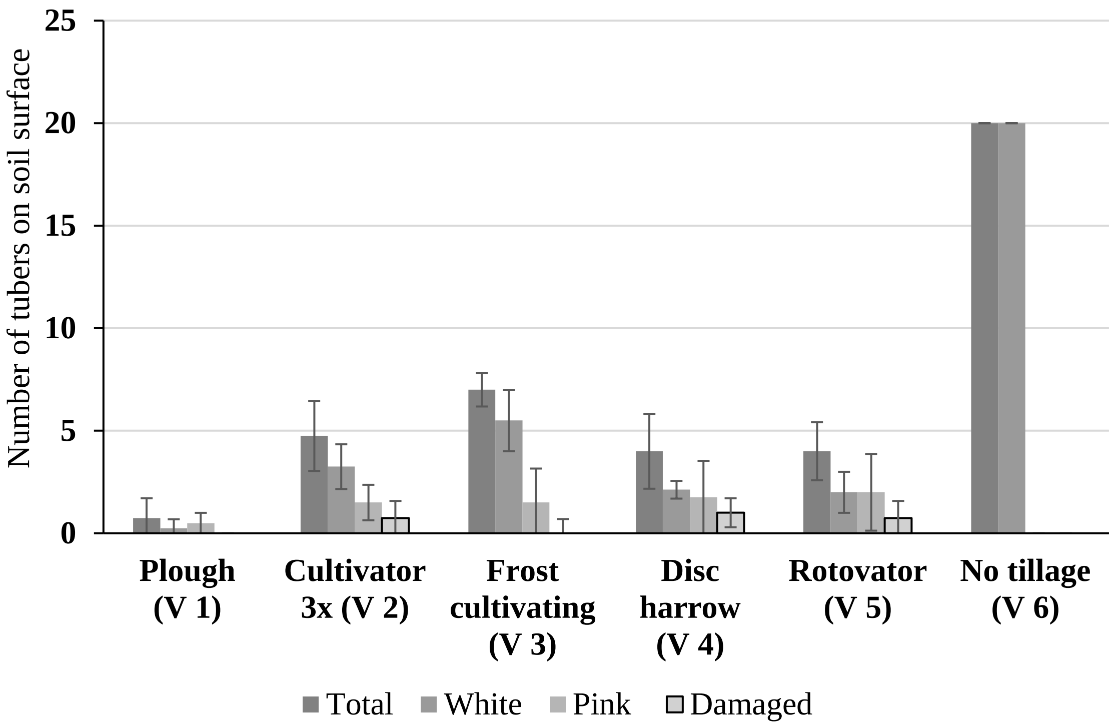


**Figure 10:** Number of tubers on soil surface after tillage for different tillage variants (V 1 - V 6) in field experiment five (F 5). Presented are the mean number of totals, white (on soil surface before tillage), pink (buried before tillage) and damaged tubers in every tillage variant with standard deviation.

## 5.3 The effect of tillage on the number of volunteer potato plants

### 5.3.1 Summarized evaluation of all field experiments

The results show the significant effect of tillage on the number of volunteer potato plants in spring between the tillage variants (V 1 - V 6), comparing the data of all five field experiments (figure 11). The tillage variants frost cultivating and no tillage showed a significant reduction of the volunteer potatoes grown on the field strips in spring compared to the plough and the rotovator variant. The variants plough and rotovator showed significantly most volunteer potatoes. The tillage variants cultivator 3x and the disc harrow differed not significant with other the tillage variants.

The plough variants showed an average of 14.4 (± 5.9) volunteer plants. Following 36.0 % of the tuber in the plough variant survived the winter. In the rotovator variants survived an average of 14.3 (± 6.5) volunteer plants, 35.8 % of all tuber in these plots. The tillage strips tilled by the disc harrow showed an average of 9.6 (± 5.0) volunteer plants followed by the variants tilled with the cultivator 3x with an average of 9.4 (± 6.0) volunteer plants. The variants with frost cultivating showed an average of 8.6 (± 6.1). The lowest number of volunteer potatoes was found in the variants were no tillage was done, with an average of 8.0 (± 4.8) volunteer plants per strip. In the no tillage variant survived 20.0 % of the tubers the winter.

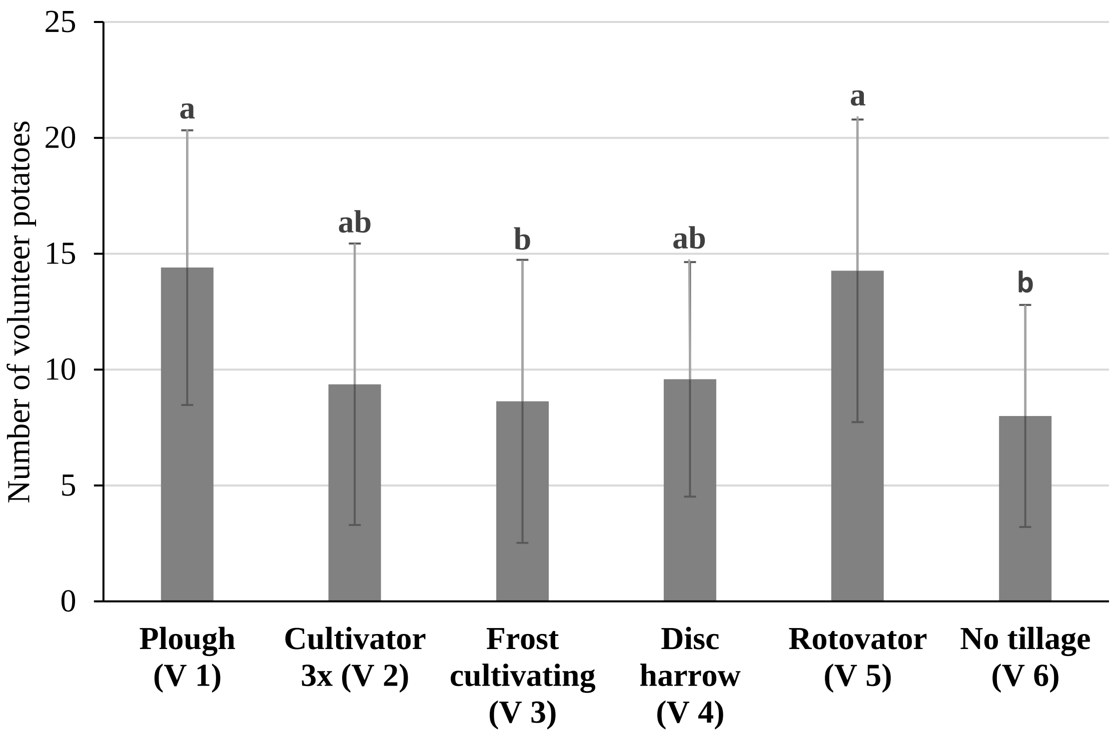


**Figure 11:** The effect of post harvesting tillage on the number of volunteer potato plants in spring. Shown are the summarized results of all five field experiments (*n* = 19). Different letters indicate significant differences at a probability level of 95 %.

### 5.3.2 Separated evaluation of the field experiments

The evaluation of the effect of tillage on occurrence of volunteer potatoes was also calculated for each field experiment independently (figure 12). Each field experiment showed different pattern comparing the results of the other experiments. In F 1 the detected numbers of volunteers per tillage strip was general lower compared to the other field experiments. The V 1 showed most volunteers compared to the other tillage variants in F 1 and differed significantly with the number of volunteers in cultivator 3x variant. The V 1, V 3 -V 5 did not differ significantly in the F 1. An average of 6.8 (± 2.7) volunteer potatoes was count in the V 1 of F 1. Second most volunteers in F 1 showed the V 5 with an average of 5.8 (± 2.6), followed by the V 6 with an average of 5.0 (± 0.7) volunteer potatoes. In descending order, the V 3 showed an average of 3.5 (± 0.5) volunteers and the V 4 showed an average of 2.8

(± 0.8) volunteers. The fewest number of volunteers in F 1 showed the V 2 with an average of 2.0 (± 0.7) volunteer plants per tillage strip.

In F 2 most volunteer potatoes were found in the plough variants with an average of 21.7 (± 1.7) volunteer plants. Compared to the other plough variants of F 1, F 3 - F 5 this was the highest number of counted volunteer plants. In F 2 the plough variant differed not significantly with the V 2 and V 5, but with V 3, V 4 and V 6. The rotovator variant showed second most volunteers with an average of 20.0 (± 2.7) plants in F 2, in descending order followed by the V 2 with an average of 14.3 (± 5.0) volunteers. The V 3 differed not to any other tillage variant. The V 3 showed an average of 13.3 (± 20) volunteer plants per tillage strip followed by the V 4 with an average of 13.0 (± 2.5) volunteers. The lowest number of volunteers in F 2 was detected in V 6 with an average of 11.0 (± 1.2) volunteer plants.

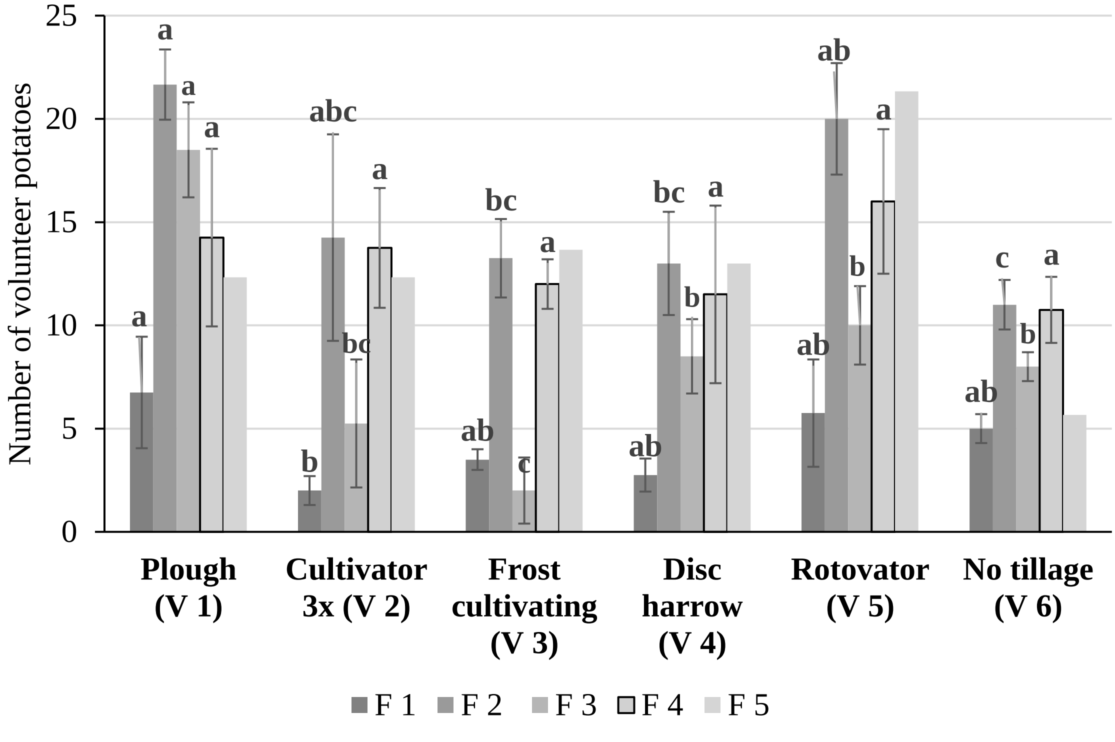


**Figure 12:** The separated results of the number of volunteer potato plants in spring effected by different tillage variants (V 1 - V 6) for the five field experiments (F 1 - F 5). Different letters indicate significant differences at a probability level of 95 %.

Also, in F 3 significant effects of tillage on occurrence of volunteer potatoes could be evaluated. The plough variant showed most volunteer plants compared to the other tillage variants and differed significantly with all other tillage variants. The V 4 - V 6 differed not significantly with each other but differed significantly with V 3 and V 1. The V 2 and V 3 differed not significantly with each other. V 3 differed significantly with other variants, except V 2. In V 1 an average of 18.5 (± 2.3) volunteer plants could be evaluated in tillage strips. In descending order, the V 5 showed an average of 10.0 (± 1.9) volunteer potatoes, followed by the V 4 with an average of 8.5 (± 1.8) and V 6 with an average of 8.0 (± 0.7) volunteer plants. The V 2 showed an average of 5.3 (± 3.1) volunteer plants on tillage strip and in V 3 fewest number of volunteer potatoes was identified with an average of 2.0 (± 1.6) volunteer plants.

In F 4 and F 5 no significant effect of tillage on occurrence of volunteer potatoes could be evaluated. The average most volunteer potatoes showed the V 5 with an average of 16.0 (± 3.5) in F 4 and an average of 21.3 (± 3.3) volunteer plants per tillage strip in F 5. In F 4 second most volunteer plants could be detected in the V 1, with an average of 14.3 (± 4.3) volunteers. Followed by V 2 with 13.8 (± 2.9) volunteers per tillage strip. In descending order, the V 3 showed an average of 12.0 (± 1.2) volunteer plants followed by the V 4 with an average of 11.5 (± 4.3) volunteers. The fewest number of volunteers in F 4 was detected in V 6 with an average of 10.8 (± 1.6) volunteer plants per tillage strip. In F 5 second most volunteer plants were detected in V 3 with an average of 13.7 (± 7.9). This value is nearby the average of V 4 with 13.0 (± 5.4) and V 1 and V 2 with an average of 12.3 (± 3.3, ± 3.9) volunteer plants per tillage strip. The lowest number of volunteer plants in F 5 could be detected in V 6, with an average of 5.7 (± 4.6) volunteer potatoes per tillage strip.

## 5.4 Weather results

### 5.4.1 Temperature results

The temperature was calculated by the DWD with hourly values for the soil surface and at 10.0 cm depth in soil. Figure 13 represents the mean night temperatures on soil surface. This figure shows the clear differences in frost condition in all five field experiments. While the mean night temperature in F 1 to F 3 often was lower than 0.0 °C, the temperature in NRW and lower Saxony was not that low. The blue and the red line is most of the time under the green and lilac line. The lowest calculated hourly temperature on soil surface in F 1 and F 2 was - 5.6 °C on 13$^{th}$ February 2020. In F 3 the lowest temperature was - 9.9 °C on 31$^{st}$ March 2020 and in F 4 - 3.8 °C on 2$^{nd}$ January 2020. In F 5 only a lowest temperature of - 3.0 °C was calculated on soil surface on 2$^{nd}$ January 2020.

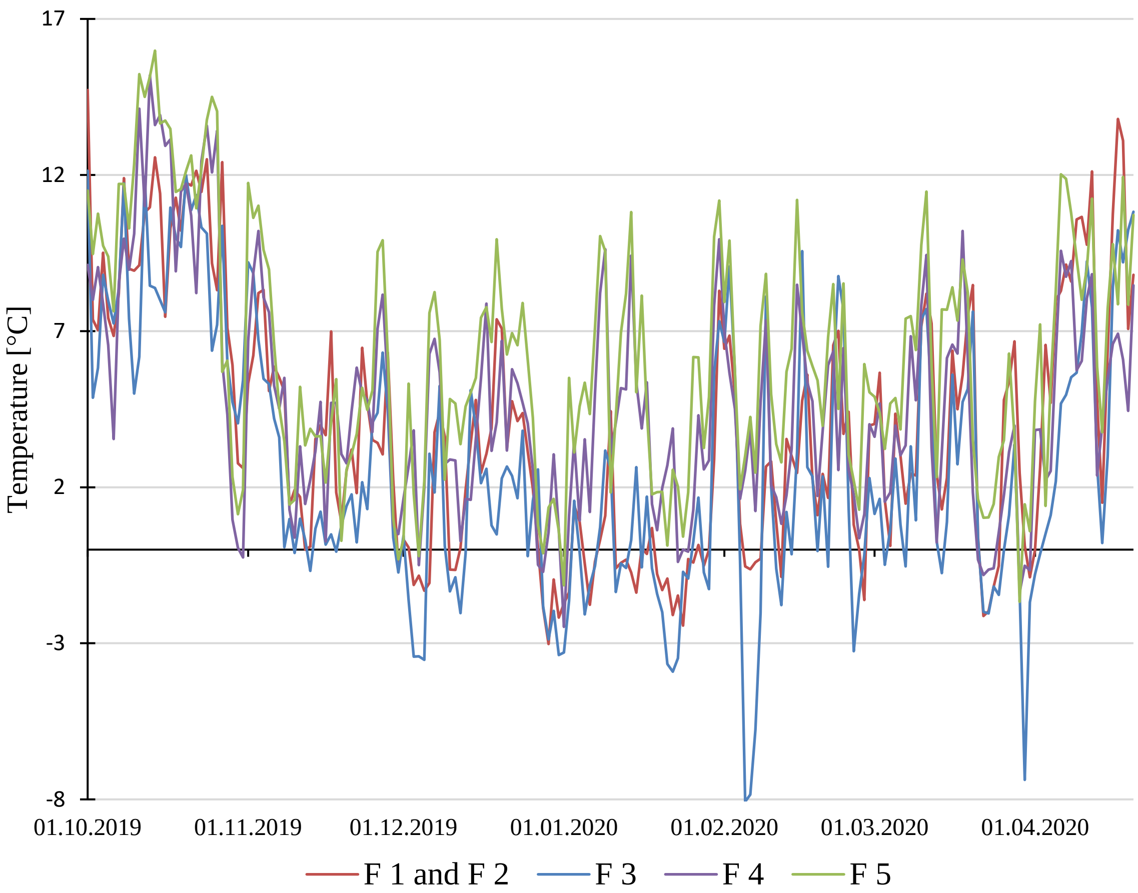


**Figure 13:** Mean night temperature on soil surface from 01.10.2019 to 20.04.2020. The temperature was calculated for the five field experiments (F 1 - F 5). Shown are the mean night temperatures calculated by hourly data from 9 pm to 6 am.

The soil temperature 10 cm depth in soil show a clearly different picture (figure 14). The temperature did not fall often below 0.0 °C, also not in F 1, F 2 either in F 3. In this figure it is shown that the blue and red line is under the green and lilac line, indicating a general lower temperature in F 1 and 2 and in F 3. The lowest calculated temperature in F 1, F 2 and F 4 was - 0.04 °C. In F 1 and F 2 this temperature was reached on 25th January 2020. In F 4 this temperature was reached on 2nd January 2020. In F 3 - 2.2 °C was the lowest calculated temperature measured on 24th January 2020. In F 3 the temperature 10.0 cm depth in soil did fall under - 1.0 °C before the strongest frost occur. In F 5 the calculated temperature 10.0 cm depth in soil did not fall below 0.0 °C. The lowest temperature was 0.5 °C on 2nd January 2020 10.0 cm in soil (figure 14).

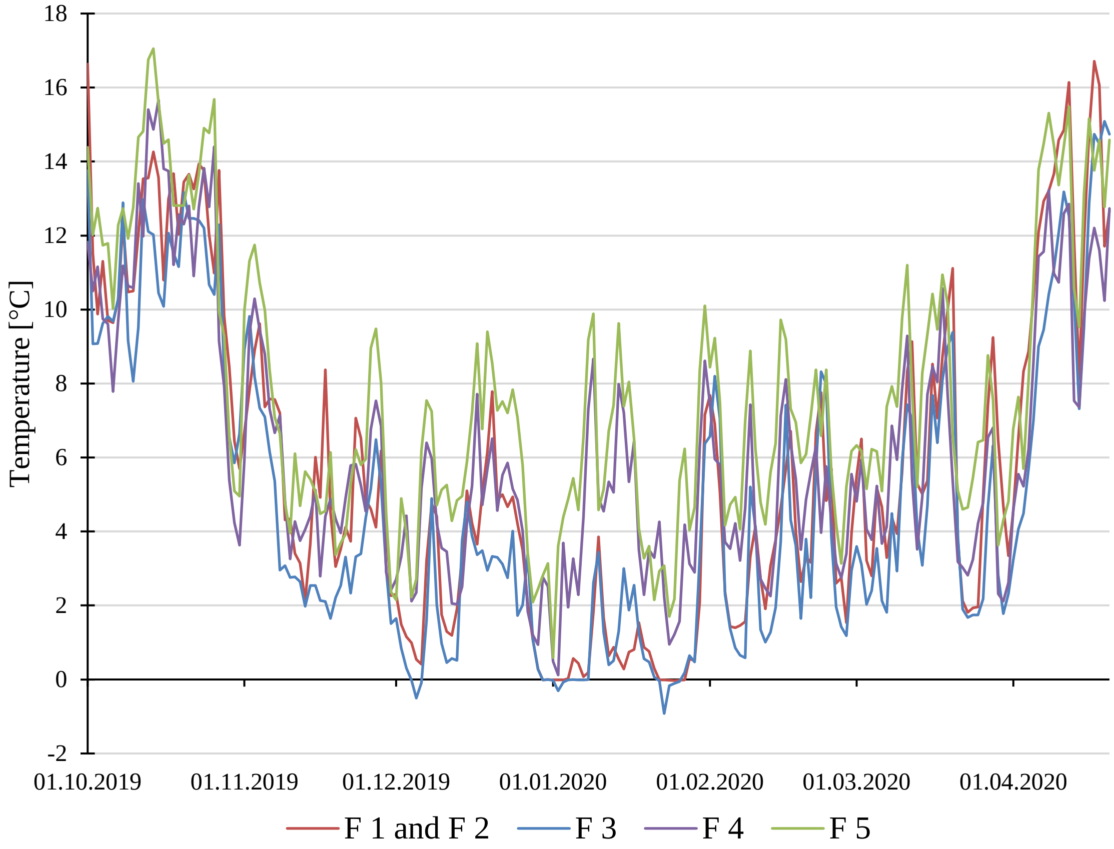


**Figure 14:** Mean night temperature 10.0 cm under soil surface from 01.10.2019 to 20.04.2020. The temperature was calculated for the five field experiments (F1 - F 5). Shown are the mean night temperatures calculated by hourly data from 9 pm to 6 am.

The number of frost hours of each experiment are shown in table 6. In F 1 and F 2 725 hours of temperature lower than 0.0 °C could be calculated for the soil surface. 10.0 cm depth in soil 263 hours of a temperature lower than 0.0 °C could be calculated. On soil surface in F 1 and F 2 257 hours of temperatures below - 1.0 °C were calculated, whereat 10.0 cm in soil no hour with a temperature lower than - 1.0 °C was detected. 80 hours of temperatures lower than - 2.0 °C and 15 hours with a temperature lower than - 3.0 °C could be calculated on soil surface of the F 1 and F 2. In Baden-Württemberg (F 3) 976 hours were counted with a temperature lower than 0.0 °C on soil surface. Ten-centimetre depth in soil 412 hours of frost with a temperature lower than 0.0 °C could be counted in the period of the 01st October 2020 to 20th April 2020. With a temperature lower than - 1.0 °C 494 hours were counted on soil surface and 17 in a depth of 10.0 cm in soil. In Baden-Württemberg 291 hours of temperatures lower than - 2.0 °C degree were counted on soil surface, 46 hours 5.0 cm depth in soil and 3 hours 10.0 cm depth in soil. Temperatures lower than - 3.0 °C were calculated 169 hours on soil surface, 6 hours 5.0 cm depth in soil, but no hour in a depth of 10.0 cm.

**Table 6:** The number of frost hours below the shown temperature from 01.10.2019 to 20.04.2020 in field experiments for two different soil layers, calculated for the mentioned DWD stations.

| | **Hours with temperature[°C]** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **< 0** | | **< - 1** | | **< - 2** | | **< - 3** | |
| | **Placement under soil surface [cm]** | | | | | | | |
| **Experiment** | **0** | **- 10** | **0** | **- 10** | **0** | **- 10** | **0** | **- 10** |
| F 1 and F 2 | 725 | 263 | 257 | 0 | 80 | 0 | 15 | 0 |
| F 3 | 976 | 412 | 494 | 17 | 291 | 3 | 169 | 0 |
| F 4 | 241 | 21 | 43 | 0 | 13 | 0 | 4 | 0 |
| F 5 | 119 | 0 | 15 | 0 | 7 | 0 | 0 | 0 |

In F 4, 241 hours with a temperature below 0.0 °C were calculated for the soil surface and 21 hours in a depth of 10.0 cm. On soil surface in F 4 43 hours of a temperatures below - 1.0 °C were calculated and no hours of a temperature below - 1.0 °C in a depth of 10.0 cm. In F 4 13 hours of a temperature below - 2.0 °C and 4 hours of a temperature below - 3.0 °C be were calculated. In F 5 119 hours with temperatures below 0.0 °C were count on soil surface and no hour of frost 10.0 cm in soil. In F 5 on soil surface were 15 hours of a temperature below - 2.0 °C and 7 hours of a temperature below - 3.0 °C calculated.

### 5.4.2 Precipitation

The precipitation during experimental setup was measured and the sums were calculated for each field experiment. The highest precipitation sum was calculated at the DWD weather station in Villingen-Schwenningen, with 519.1 $mm^3$ at placement of F 3. At the DWD station in Borken (F 5) a total sum of 512.4 $mm^3$ precipitation could be calculated. Less precipitation was calculated at the DWD Station in Soltau (F 4) with 474.5 $mm^3$ during the experiment. The lowest precipitation was calculated at the DWD station in Fürstenzell. Only 363.2 $mm^3$ were calculated for F 1 and F 2.

# 6 Discussion

## 6.1 The effect of tillage on vertical distribution of tubers in soil

Due to the significant decrease of soil frost events, which occurred predominantly in the eastern central German uplands (Kreyling and Henry 2011) the problems with volunteer potatoes increase. With the decrease of soil frost events, potatoes in deeper soil layers are protected from freezing. Generally, there is some research on the distribution of the tubers in soil after harvesting (Lutmann 1977, Newberry and Thornton 1998, Demmel et al. 2019). But only Lumkes and Beukema (1973) measured and published the impact of tillage on the distributions of tubers in soil. Therefore, the present work investigated the impact of different tillage implements on the distribution of volunteer tubers in soil. Since each tuber which is transported closer to soil surface by tillage is more susceptible to freezing over winter, tillage can partially reduce the volunteer problem.

The observations at harvest and spring on the vertical distribution of tubers in soil demonstrated that different tillage equipment significantly affected the transport of tubers into different soil layers. Further, results have proved that ploughing buried potato tubers significantly deeper into soil than other tested implements. This was also confirmed with hypothesis 1) part a) that stated that the plough buries tubers significantly deeper than other tillage implements. This was consistent with previous investigations of researchers who found that the plough buries tubers more deeply into soil (Lumkes and Beukema 1973, Rahman 1980, Demmel et al. 2019). Already in 1980 Rahman claimed in a review about volunteer potatoes that ploughing buries tubers deeper than straight-tine cultivation. Thus, the plough after harvest protects volunteer potatoes from freezing and increases their survival.

The harvest assessment showed no significant difference in depth distribution of tubers in soil between the tested tillage implements except the plough because the observation was only done in one repetition. Whereas, the spring observations on the stolon length, done in 15 repetitions, showed that the rotovator placed the tubers significantly closer to soil surface than the plough. This confirms the hypothesis 1) part b) that the rotovator places the tubers in shallow level under soil surface, significantly higher than all other implements. Unfortunately, available literature that investigated the effects of the rotovator on the volunteer potatoes, did not measured the depth of the tubers after tillage (Thomas and Smith

1983). However, Demmel et al (2019) (*unpublished results*) did a similar harvest observation of the tuber depth distribution after tillage. They investigated the difference between the cultivator in different cultivating depth, an implement combination with discs and cultivator shares, the mouldboard plough and a disc harrow. In contrast to this experiment, they did not test the rotovator and a variant with no tillage. Nevertheless, they also found that other tillage implements, except the plough had no significant impact on tuber depth distribution in soil, while the mean depth was varying with the tillage implements (Demmel et al. 2019).

Moreover, the present results indicated that repeated cultivating tended to transport the tubers closer to soil surface than cultivating only once. The description of the working principle of the cultivator gave a reason to assume that the vertical up forces of the cultivator transport potatoes to surface with more crossings (Berntsen and Berre 1993, Fielke et al. 1993). However, the investigation of Lumkes and Bekema (1973) with a fixed-tines cultivator on tuber movement in soil stated that the vertical movement of the potatoes tubers was only slight. They did also some experiments with pigmented tubers and measured the depth of tubers in soil after tillage but examined only the variant cultivating once. However, results of the present experiment demonstrated that the rotovator laid the tubers closest to soil surface while repeated cultivating showed a similar trend. The closer the potato tubers were brought to soil surface by tillage the more susceptible they were to the following soil frost. Therefore, it can be concluded that tillage with the rotovator can enhance the chance of freezing of these tubers over winter.

## 6.2 The effect of tillage on the number of tubers on soil surface

Potato tubers laying on the soil surface are exposed to freezing and do not survive winter which is the result of their decaying over winter. Therefore, the number of tubers on soil surface is an important factor in the assessment of tillage implements in control strategies of volunteer potatoes. The number and the consideration of the soil layer the potato was before tillage provides information about the working method of the tillage implement on potato tubers. These experiments demonstrated that tillage after harvesting of potatoes significantly affected the number of potatoes remaining on soil surface. In the no tillage variant, most tubers remained on soil surface while the plough removed most from soil surface in deeper layers.

As mentioned in previous chapter (chapter 6.1), ploughing buried tubers more deeply in soil than other tested tillage implements. Additionally, the available data showed that ploughing lead to significantly fewer potatoes on soil surface compared to all other tested tillage implements. Nevertheless, these results were also reported by Lumkes and Beukema in 1973. Their investigations showed that, if the tubers were placed on soil surface before tillage, they were transported by tillage into a soil depth of 20.0 - 40.0 cm. This was a reduction of the number of tubers on soil surface. If tubers were buried 5.0 cm into soil before ploughing, the tubers were transported into a soil depth of 15.0 - 40.0 cm. In addition, Lumkes and Beukema (1973) revealed that if tubers were already buried 15.0 cm in soil, fewer tubers were transported to soil surface by tillage. They also claimed that the number of tubers on soil surface was much lower in ploughing variants than in the cultivator version. Similar to this, the present experiment showed that tubers laid on the surface before ploughing were buried and the buried tubers were partially transported to the surface in small numbers.

When generalizing data over all five experiments, results indicated that ploughing removed tubers from soil surface into deeper soil layers. But slightly different results were obtained by the separated results. Comparing all ploughing variants (F 1 - F 5), the number of tubers on soil surface in lower Saxony was noticeable (table 4). In lower Saxony the used Rabe Super Albatros plough (Grégoire-Besson GmbH, Bad Essen, Germany) lead to highest number of tubers on soil surface compared to the other four experiments. In consequence, as all ploughs were driven with the same speed and depth, only the interbody width could has influenced the number remaining tubers on surface. Following, this result in F 5 was due to the small interbody clearance of 40.0 cm between the continental bodies of the Rabe Super Albatros (Grégoire-Besson GmbH, Bad Essen, Germany). The other ploughs used in these experiments had an interbody clearance of 100.0 cm. The smaller interbody clearance lead to the result that soil was turned more than once. Ploughing buries upper soil segments deeper in soil, compared to soil segments placed at a depth of 10.0 cm in soil (Lumkes and Beukema 1973, Ucgul et al. 2017). Thus, when the soil was turned several times because of a small interbody clearance the buried top soil including potatoes were transported back to surface. In contrast, in Baden-Württemberg no tuber was found on soil surface in the plough variants. The Kverneland 2500 isobus plough (Kverneland Group, Klepp, Norway) worked with six continental bodies on 3.0 m. This serves enough space for each continental body to turn the soil exactly once and that ensures burial of potatoes. Therefore, the setting of a soil tillage implement can also influence on the occurrence of volunteer potatoes.

For the summarized data no significant effect was found on the total number of tubers on soil surface between the other tillage variants (V 2 - V5). However, compared to plough all variants showed significant higher number of tubers on soil surface than the plough variant. Thus, hypothesis 2) part b) and part c) could also be confirmed. These hypotheses stated that frequently cultivating and the tilling with the rotovator had a significant impact on the number of tubers remaining on surface. The data showed that all cultivating variants lead to a higher number of tubers on soil surfaces compared to ploughing. Whereas, the results of Demmel et al. (2019) approved these results. They found also only tendencies that the cultivator led to a higher number of tubers on soil surface than the disc harrow or the combined cultivator. In contrast to the present experiment, Demmel et al. (2019) did not test frequent crossings with the cultivator. Although no significant effects could be observed between the tillage variants of this experiment, some tendencies could be detected. On the one hand, crossing once led to a higher number of total tubers on soil surface than frequent cultivating. On the other hand, frequently crossing led to a lower number of total tubers on soil surface but to a higher number of buried tubers on soil surface. Thus, it can be assumed that frequently crossing incorporated more potatoes than the vertical up forces of cultivating transported buried potatoes to soil surface. This assumption could be confirmed by results of Lumkes and Beukema (1973). Their investigations also showed a very slow vertical movement of the potatoes tilled by a fixed-tined cultivator. Results of the present experiments stated that crossing once buried 59.5 % of tubers laid on soil surface and transported 7.0 % of buried potatoes to soil surface. Frequently crossing buried 62.0 % of tubers and transported 13.3 % of buried tubers to soil surface. Therefore, the total sum of tubers on soil surface, which were susceptible to freezing, was higher in the frost cultivating at time of the harvest evaluation. Cultivating buried more tubers than transported to soil surface. Considering that a cultivator is normally used to incorporate stubble and plant residues into soil (Esterl and Knittel 1996, pp. 113), it is obvious that a cultivator is not suitable to transport potatoes up to the soil surface in higher rates. However, in some literature it is also stated that the cultivator can transport potatoes to soil surface with bigger steel, or with a blunter cutting edge because of an increase of the vertical up forces (Sarec and Sarec 2015, Fielke et al. 1993) but, in present experiment the variation in the thickness of steel or different cutting edges were not part of the investigation.

Furthermore, when the five experiments were considered separately the cultivator variants in Baden-Württemberg were noticeable because of the high number of tubers on soil surface after harvest tillage. In this cultivator variants on average more potatoes were found on soil surface, than in the other four field experiments. In this experiment the Horsch cruiser 6 XL (HORSCH Maschinen GmbH, Schwandorf, Germany) was used. In contrast to the other cultivators, the cruiser has six crossbeams and spring-loaded duckfoot shares. The other cultivators were equipped with two to three crossbeams and fixed tines. More cross beams led to a higher shaking effect, whereat higher vertical up forces transported light pieces and potatoes to soil surface. Moreover, the duckfoot shares had a smaller working width. According to Galant and Ingale (2017) the soil inversion increases with the width of shovels. Therefore, the combination of small duckfoot shovels on the cultivator with six crossbeams led to a higher vertical up force and a lower incorporation effect of potato tubers. Another interesting result was that in all experiments one crossing by cultivator led to more tubers on soil surface than three times of crossing, except the field experiment in Arnstorf. In the field experiment in Arnstorf the Pöttinger Synkro 3003 (PÖTTINGER Landtechnik GmbH, Grieskirchen, Austria) was used. Thus, it can be reasoned that the chisel point solo wing crowed blades mounted on the Pöttinger Synkro 3003 (PÖTTINGER Landtechnik GmbH, Grieskirchen, Austria) did not have a high incorporation effect on the heavy soil in Arnstorf and therefore transported tubers to soil surface. However, it is shown that number of potatoes which were buried first and transported to soil surface by tillage was generally higher in the variants with frequent cultivating compared to cultivating once. When considering results separated for the individual regions, these effects could not be observed for the F 4 and F 5 on sandy soil. On the very sandy soil in lower Saxony and North Rine-Westphalia no difference was found between one or frequent crossing. In general, the number of evaluated potato tubers after tillage was lower on sandy soil compared to the other field experiments. This was due to the more pronounced bury effect in sandy soil. Clods on soil surface led to a higher soil surface where potatoes can be detected. In sandy soil, the soil surface is even and therefore eye-detected surface was smaller. Considering this aspect, the results led to suspect that the tubers buried in sandy soil before tillage were also nearer to soil surface.

The present experiments showed that tillage with rotovator led to second most tubers on soil surface, after no tillage. Therefore, the hypothesis 2) part c) could be confirmed which stated that the rotovator lead to a significantly higher number of volunteers on soil surface compared to ploughing. Especially in F 2 the number of total tubers on soil surface in the rotovator variant was significantly higher compared to the other variants, except the no tillage variant. Thus, in these variants significantly more potatoes were susceptible to frost and animals over winter which may led to less volunteer potatoes in the next year. Also, the special equipment of the used Celli Tiger 190 (CELLI S.p.A., Forli, Italia) had affected this result. This rotovator had no roller afterwards and the guard could be opened. This led to a throwing backward effect with a flight curve which implies that small light pieces were thrown on surface while bigger heavier pieces were buried deeper in soil. Therefore, in these variants more potatoes could be found on the soil surface. In contrast to F 3 - F 5 where a roller was behind the rotovator and the guards could not be opened. Consequently, the potatoes were thrown against the closed guard and incorporated into soil by the roller (Gommel 1967, pp. 131). Crushing the guard is an advantage for crumbling of soil clods but it did not have an effect on infringement of potatoes.

Opposite effects were observed in the F 5 in NRW where the variant with the rotovator showed less potatoes on soil surface. This confirms that besides the type of tillage implement also the equipment of rotovator also had an impact on the number of tubers on soil surface. While the Celli rotovator led to a high number of potatoes on soil surface, older rotovator variants like in F 4 and F 5 showed less potatoes on soil surface. This result could be verified by old experiments of Thomas and Smith in 1983. Thomas and Smith did not evaluate the tubers after tillage but they claimed that the used rototiller showed no significant impact on volunteer potato occurrence in next year. The different working methods of the rotovators become even clearer when considering the results of the white tubers on soil surface of every experiment in the rotovator variants. In F 1 - F 2 more than twice the number of white potatoes was found on soil surfaces in the rotovator variants than in F 4 and F 5. This showed that incorporations performance of the rotovator used in F 1 and F 2 was lower than for the rotovator used in F 4 and F 5. Interestingly, the use of the rotovator in F 1 - F 3 resulted in obvious more pink tubers on soil surface compared to all other tillage variants. In F 2 and F 3 the difference was significantly. Thus, the hypothesis 3) can be confirmed that the new and more aggressive rotovators led to a higher number of potato tubers on soil surface than all other tested tillage implements. The more potatoes were on soil surface the more were exposed to frost or other damaging effects. Further, it can be suggested that less volunteer potatoes ca be detected in the rotovator variants of F 1 - F 3. On the one hand tillage can support the exposition of volunteer tubers to frost by transporting them closer or direct to soil surface. On the other hand, no tillage implements transported more potatoes to soil surface than in the no tillage variants. To sum up, while ploughing reduced the number of tubers remaining on soil, the variant with no tillage showed the most tubers on soil surface.

Thus, it can be stated that no type of tillage implement transported more potatoes to the soil surface than its buried. In conclusion the no tillage variant seemed to be the best variant to favour the decaying of potatoes over winter.

## 6.3 The effect of tillage on damage status of potato tubers

The more intensive the tillage after harvesting, the larger the effect of tillage on number of potatoes decaying during winter due to damages (Lumkes 1979). This common statement is confirmed by Wright and Taylor (1921). Wright and Taylor (1921) investigated the impact of jarring potatoes on the susceptibility to frost damages and described that injured potatoes already freeze at higher temperatures. Their experiments were done with hand injured potatoes and gave no hint which tillage implement could best be used for damaging the potatoes. Up today, there is no literature available dealing with investigations on evaluating the damage status of volunteer potatoes after tillage. In this experiment the damage status of the potato tubers on soil surface was evaluated by counting each potato piece in harvest after tilling with the different implements (V 1 - V 6). Results over all five experiments showed the significant highest number of damaged tubers on soil surface in the rotovator variant, compared to all other tillage variants. This confirms the hypothesis 3) that tillage with a rotovator lead to a significantly higher number of destroyed potato tubers on soil surface. Therefore, only the effects of this variant will be discussed in detail in the following section.

The rotovator was the only active working implement, driven by the power of the take-off shaft. Due to its working method, the rotovators penetrated the soil with protractors 200 - 318 times per minute, which led to an intensive crushing and crumbling effects of clods including the potatoes. Already in 1967, Gommel pointed out the crushing effect depends on driving speed and number of knifes penetrating soil during roller rotation. Following the density of the rotovator can be calculated by counting the number of impacts of protractor per square meter (Gommel 1967, pp. 131). Considering results of the damaged potatoes separated for individual field experiments there is a pattern notable. The more aggressive the rotovator penetrated the soils the more damaged tubers were on soil surface. Important for further considerations is to keep in mind that, in F 1, F 3 and F 5 no significant difference in the number of damaged potatoes on soil surface was found between all tillage implements. In F 2 in Vilshofen the rotovator exhibited significantly more damaged potatoes on soil surface. In F 4 the rotovator demonstrated significantly more damaged potato tubers on soil surface than all other variants, except the disc harrow variant. In F 2 in Vilshofen the Celli Tiger 190 was inserted that rotates with 1000 rotations per minutes of the shaft. This led to a soil and potato penetration of 318 times per minute with 72 protractors. The density calculated is following 7 632 penetrations per minute. With a driving speed of 2.0 km per hour the rotovator penetrated every square meter of soil 231.0 times. In comparison, the breviglieri maxi-double 630 penetrated the soil in this experiment 165.4 times, the Kuhn EL 201 penetrated 152.7 times and the Krones RS at least 145.5 times the soil per square meter. The penetrating density of soil per square meter demonstrated that the Celli rotovators were the most aggressive implements. In 1979, Lumkes stated that the most intense and aggressive tillage implement should be used after harvesting potatoes to control volunteers in next year. However, he did not mention the implement which mostly attended to destroy potatoes. In addition, the clods of the heavy soil in Vilshofen increased the cutting effect also because every clod interacted as counter cutting edge. Following, the number of damaged potatoes in F 2 was also higher than in all other four experiments. Due to the very high damage status of the tubers, it could be assumed that the rotovator led to the highest mortality of tubers over winter in F 2.

In F 4 the rotovator variant indicated significantly more damaged potatoes than all other variants, except the disc harrow variant. Compared with F 2 the total number of damaged potatoes was general very low. However, the used disc harrow in F 4 was the Amazone Catros 3001 (AMAZONEN-WERKE H. Dreyer GmbH & Co. KG, Hasbergen, Germany) which differed from other used disc harrows. The equipped discs had great cutting angle in front row of the discs with 17 ° and a low cutting angel in the back row of the discs with 14 °. Esterl and Knittel (1996) stated, if the disc blocks are levelled, the discs have a predominant cutting effect. The more inclined the angle of the discs in driving direction the more intense is the crumbling and mixing effect. The combination of two different cutting angles of the discs led to a mixing effect which that transported the potatoes closer to surface. With a second row of discs the harrow cutted these potatoes. Moreover, the Amozone Catros had a very small line distance which enhanced the tilled space of soil and therefore the chance of cutting these potatoes. In conclusion, the results showed that the rotovator can enhance tuber mortality over winter by intensively destroying potatoes, however, the intensity of the rotovator is crucial for the success.

## 6.4 The effect of tillage on the number of volunteer potatoes in next year

The experiments demonstrated that post harvesting tillage significantly affected the number of volunteer potatoes in next year which confirms the hypothesis 4). In addition, already Thomas and Smith in 1983 stated that timed tillage combined with a cover crop could be as effective as chemical treatments in reducing volunteers. Whereas Demmel et al. (2019) in their experiment showed that the tested tillage implements have no significant impact on volunteer plants in next year. Further, Newberry and Thornton (2004) did field experiments from 1998 to 2001 and presented that the experiments in one year showed no results and in other years valid results. To take account for highly variable results reported in literature, this experiment was done in five replicates at four different locations. Even the survival rates of volunteer potatoes vary from year to year, but in general most volunteer potatoes survive in harvest-ploughed fields. The present experiment proved that 36.0 % of the in harvest on field remaining potato tubers survived the winter. This was consistent with previous investigations of Boone and van der Elst (1977) and Lumkes (1979) who disserted that 20.0 to 50.0 % of the remaining tubers in spring germinate.

However, the present experiments have shown that no tillage after harvesting significantly reduced the number of volunteer plant in next year, compared to common ploughing. The no tillage variant showed also the highest number of tubers on soil surface in harvest observations. Tubers on soil surface do not survive winter and therefore the on field remaining tubers are should remain on soil surface (Rahman 1980, Pickny and Scheid 1999, Meyer 2015). 50.0 % of the tubers were placed on soil surface in the no tillage variant and 50.0 % were buried in 10.0 cm depth in soil. Unlike the experiment, potato field experiments have shown that after harvesting potatoes in practice only 20.0 to 30.0 % of the tubers remain on soil surface (Lutmann 1977, Newberry and Thornton 1998). The other tubers were buried up to 20.0 cm depth in soil and germinate in next year. Following, if the no tillage variant should be tested in further field experiments again, the number of the tubers on soil surface should be decreased due to the results of the experiments of Lutmann (1977) and Newberry and Thornton (1998). However, the no tillage variant was a good variant to show that the main aim should be to transport the buried tubers up on soil surface, not only close under soil surface.

The results have shown that the rotovator places the tubers in shallow level under soil surface but in spring significant most volunteer potatoes germinated in these variants. In F 3 most frost hours in soil could be calculated compared to the other field experiments. While on soil surface 494 hours of degrees under - 1.0 °C could be calculated, only 17 hours 10.0 cm depth in soil were observed with that temperature. In connection with the results of the evaluation of the depth distribution of the tubers in the soil, it can be assumed that potato tubers also survive temperatures below - 1.0°C in the soil. The stolon length in F 3 varied between 1.0 cm - 30.0 cm. These results contradict the statement of Muller- Thurgau in 1880, which purported that the ultimate freezing point of potatoes is - 1.0 °C (Boydston 2006). The lowest temperature in coldest F 3 in a depth of 10.0 cm was - 2.2 °C. Jones et al. (1919), Wright and Taylor (1921), Wright and Harvey (1927) and Boydston (2006) concluded that the freezing point of potatoes is between - 1.0 °C and - 2.2 °C. Following, all potatoes in the depth to 10 cm should be damaged by frost. This in contrast to results of this experiment that showed potatoes in soil layers with temperatures between - 1.0 °C and - 2.2 °C still germinate. Therefore, these results agree with the conclusion of Jones et al. (1919) and Boydston et al. (2006) that potatoes must be supercooled first to temperatures between - 3.0 °C and - 7.0 °C before an exotherm occur and the potatoes unable to sprout. Moreover, the mean stolon length in F 3 was longer than 5.6 cm but potatoes in soil layers of 1.0 cm to 5.0 cm were still found. The lowest temperature in a soil depth of 5.0 cm was - 3.6 °C. While potatoes where found in a depth up to 5.0 cm in soil, it can be concluded that an initial frost for an exotherm had to be lower than - 3.6 °C to completely freeze the potatoes.

Furthermore, in F 3 in a soil depth of 5.0 cm 46 hours of frost with temperature below - 2.0 °C were reached but also the potatoes germinated from these soil layers. Therefore, these results contradict with the thesis of Lumkes (1974) that potatoes are killed by exposure of 50 accumulated degree frosts below - 2.0 °C. The present results of this experiment showed with the measurement of the stolon length in spring that in this layer up to 5.0 cm in soil tubers germinated in F 3. Nevertheless, on one hand the measurement of the stolon length was not the exact depth of the tuber in soil, because the stolon could attach to the upper or lower end of the tuber. On the other hand, the measurement of the stolon length was a good estimate of the depth of the tuber in the soil, as only small calibrated tubers with a diameter between 2.8 cm and 3.5 cm were selected for this experiment. Therefore, the measured stolon length assumed to deviate not much from the tuber depth in soil. It also varies in all variants, so that the difference between the variants was eliminated. However, in this refutation it must bear that this result was turned out only in one field test in one year. The other field trials had not reached these 50 frost hours in soil. Furthermore, the weather station in F 3 was 24 km away from the field experiment and the soil temperature was not measured but calculated.

Moreover, also frost cultivating reduced the number of volunteer potatoes significantly compared to common ploughing. The hypothesis 4) part a) that frost tillage reduces significantly the occurrence of volunteer potatoes in next year compared to the plough, therefore is confirmed as correct. Frost cultivating led to an exposure to the harvest weather of the 50.0 % on soil surface remaining tubers. Following at one frost event the cultivator jarred the upper tubers and transported some buried tubers up. If potato tubers jarred while undercooling, these tubers freeze at higher temperatures (Wright and Taylor 1921). Wright and Taylor (1921) showed this result with experiments where they undercooled potatoes while dropping them to the floor. Frost cultivating opened the soil set in autumn, thus increased the soil surface and the air content in the soil. A greater soil surface and content of air in soil led to a faster decrease of soil temperature and freezing of the soil after tillage. Therefore, frost cultivating on sandy soil in F 4 and F 5 showed no significant reduction of volunteers. On sandy soil the cavities filled with air trickled back together faster than on heavier soil. Therefore, the effect of faster cooling in deeper soil layers did not occur on sandy soil. In contrast, in F 3 the frost cultivating variant showed significantly lowest number of volunteer potatoes. The strips in F 3 were frost cultivated on 4$^{th}$ December 2019. The weather data showed that this frost event was the first in that winter season and began in the night of December 2$^{nd}$ and lasted until the December 7$^{th}$. This frost event occurred with temperatures to - 1.6 °C 10.0 cm depth in soil. Thomas and Smith (1983) reached the best results of volunteer potato reduction with ploughing the soil after the two days with temperatures below - 3.0 °C also done in December. This observation suggested that delaying frost cultivating until potato killing frost occurred would kill not only the tubers left on surface, but would also expose to freezing many additional tubers, otherwise protected by burial in the soil. However, in the present experiment it was pointed out that the refound tubers were buried deeper in the frost cultivator variants than the other variants, except the plough variant. On the one hand this could be due to completely freezing of the other tubers which were buried nearer to surface. While the temperature dropped faster in the frost cultivated variants, potatoes in upper soil layers freeze only in these variants. On the other hand, the depth distribution of the tubers in soil was dispensable because the frost events are not low enough to kill tubers. Only, that jarring while freezing led to frost susceptibility of the tubers in these variants (Wright and Taylor 1921).

Furthermore, the hypothesis 4) part b) that the rotovator reduces the occurrence of volunteer potatoes in next year compared to the plough variant can be rejected by the results of these experiments. Thomas and Smith (1983) claimed that fall tillage alone by either rotortilling or ploughing reduces incidence of volunteers about one third. This means 66.7 % of the remaining tubers survive winter. The present experiments refuted this, as only 36.0 % of the potatoes survived the winter in the ploughing variant and only 35.8 % in the rotovator variant. However, also Thomas and Smith (1983) already showed that the rotovator could not reduce volunteer potatoes compared to common ploughing. The hypothesis 4) part c) that frequently cultivating reduces the occurrence of volunteers significantly in next year, compared to common ploughing variant can also be rejected by the results of these experiments. Except in the individual consideration of the experiments, F 1 confirm this hypothesis. In F 1 frequent cultivating reduced the number of volunteer potatoes significantly compared to common ploughing. Already in the autumn evaluation this variant showed most tubers on soil surface. In F 1 the Pöttinger Synkro 3003 (PÖTTINGER Landtechnik GmbH, Grieskirchen, Austria) with three crossbars was inserted. The chisel point solo wing crowed blades mounted on the Pöttinger Synkro 3003 (PÖTTINGER Landtechnik GmbH, Grieskirchen, Austria) did not have a high incorporation effect on the heavy soil in Arnstorf. Hence it transported the potatoes up to soil surface while not buried that many other tubers. When evaluating the results of F 1, it should be noted that a generally lower number of volunteer potatoes was found in spring evaluation in this experiment. Boone and van der Elst (1977) ascertained that tubers in dense soil did not germinate as well as in loose soil. Especially during very wet conditions on a very poor soil structure they identified low oxygen concentration, which lead to suffocation of the tubers. Also, Lumkes (1979) pointed out mainly in spring when the breathability of the tubers in the soil increases, many more potatoes die by suffocation. However, the sum of precipitation in F 1 over the winter 2019/2020 was also lower than in other experiments. Chiefly, the precipitation in spring was rather small. Furthermore, the low number of volunteers in F 1 may be related to the application of glyphosate in spring. Glyphosate kills not only the aerial parts but is translocated to subterranean parts, including the early-formed daughter tubers (Rahmann 1980). If the active ingredient came in contact with the early germinated tubers, these tubers did not germinate again. Furthermore Boydston (1996) claimed that spraying of Glyphosate killed emerged potatoes, but new potato shoots emerged within two weeks. However, no potato plants were raised the ground at time of application.

It should be considered that these experiments showed significant results but were done only one year. But above all the contradiction of the thesis Lumkes (1974) of the experiments should be further investigated and spread over several years. Although in each experiment each variant was repeated four times, it has to be considered critically that each experiment was not completely randomized. The randomisation was not possible because of the low ability of the big implements to turn on small places. Therefore, the inhomogeneity of the fields could have affected the germinability of the volunteer tubers and the working method of the implements. Furthermore, since in pre-experiments the germinability with coloured tubers was determined as normal (Demmel et al. 2019), it was not stated if the colour also protected the tubers from rotting and freezing. In further experiments, some freezing chamber experiments with coloured potatoes ought to be made.

# 7 Conclusiones and Outlook

In conclusion, tillage after harvesting significantly affect the occurrence of volunteer potatoes in next year. The five field experiments showed that all tubers on soil surface decay over winter and therefore the tested no tillage variant significantly reduced the number of volunteer plants in next year, compared to common ploughing. In all experiments the temperature over winter lead to completely freezing of the potatoes in soil. Monitoring the soil temperatures at various depth in these experiments proved that minimum soil temperatures at - 2.2 at tuber depth for a brief period (Boydston 2006) and 50 h accumulated below - 2.0 °C (Lumkes 1974) did not inhibit tuber germination. The observed mortality of tubers could be assumed to be lower than in the cited literature. Nevertheless, the variant with frost cultivation significantly reduced the number of volunteer potatoes in next year compared to common ploughing. Ploughing after some frost events also expose additional tubers to lethal temperatures (Thomas and Smith 1983). Moreover, cultivating at freezing temperatures enhance air permeability in soil. The heat capacity of air is lower than water, so that cultivating reduce the soil temperature and also tuber in deeper soil layers are exposed to frost. However, in sandy soil this effect was less pronounced as cavities were less stable due to the soil texture and frost cultivating did not significantly reduce volunteers in these experiments.

Whereas, frequent cultivating after potato harvesting buried more tubers than transport to soil surface within this experiment. Buried tubers are protected by the lower temperatures which occur on soil surface and therefore these tubers germinate at higher rates next year. For this reason, frequent cultivating cannot be recommended for volunteer potato control. The disc harrow and rotovator showed the most aggressive working method and destroyed the potatoes. Nevertheless, most potato debris could germinate. Despite the rotovator has placed the tubers closest to soil surface, the freezing soil temperatures were not low enough to differentiate with mortality in different depth. Thus, frequent cultivating and the rotovator as tillage implement could not be recommended for volunteer potato control.

To validate these results tests should be repeated over several years since this study was done only one year over one winter. In further experiments the soil temperature in different layers should be logged exactly, to be able to draw very precise conclusions about the frost sensitivity of tubers in the field. In addition, chamber freezing studies should be carried out at the same time in order to determine the sensitivity to frost of the tested coloured variety of potato more precisely. The exact effect of frost cultivators on the occurrence of volunteer potatoes should also be further clarified. Because it has to be proved if frost cultivating reduces volunteers due to jarring potatoes while freezing or due to the fact that the frost penetrates deeper in soil after cultivating.

Although, differences in tillage after harvesting on mortality on potato tubers over winter were observed. To control volunteer potatoes with tillage after harvesting, the farmers have to wait until the first frosts killed the potatoes on soil surface. Then they have to cultivate during this frost period, which best last one to three days after this cultivation. However, since these experiments showed that volunteer potatoes are not entirely controlled by tillage, tillage can only be considered as part of integrated volunteer potato control. Therefore, farmers have to reduce all sources of tuber losses already in potato cultivating steps before and after harvest. To achieve for a sustainable and integrated management of volunteer potatoes all control aspects should be taken into account which should also include an adapted tillage strategy.

# 8 Literature

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# Danksagung

An dieser Stelle möchte ich mich bei all denjenigen bedanken, die mich während der Anfertigung meiner Masterarbeit unterstützt und motiviert haben.

Zuerst gebührt mein Dank Herr Prof. Dr. agr. habil. Heinz Bernhardt, der meine Masterarbeit betreut hat. Für die hilfreichen Anregungen und konstruktive Leitung meiner Ideen, was zu dem Gelingen der Versuche beigetragen hat, möchte ich mich herzlich bedanken.

Ich bedanke mich der Fördergemeinschaft der Kartoffelwirtschaft e.V. und bei Herr Röhrl dem Geschäftsführer des Landeskuratorium für pflanzliche Erzeugung in Bayern e. V. für die finanzielle Unterstützung für die Bearbeitung und Anlage der Feldversuche.

Ein besonderer Dank gilt den Landwirten die mir ihre Flächen, sowie ihre Arbeitskraft für die Anlage der Feldversuche zu Verfügung gestellt haben. Ohne ihr mitwirken wären diese Versuche nicht möglich geworden. Ebenso möchte ich meinen Freunden und meiner Familie Danken, die mir ebenfalls geholfen haben die Versuche anzulegen. Von der Versuchsstation Dethlingen gebührt Andreas Meyer ein besonderer Dank, für die Übernahme der Winter-, und Frühjahrsbonitur in Niedersachsen.

Abschließend möchte ich mich bei Valerie Sentek für das Korrekturlesen meiner Masterarbeit danken. Zu guter Letzt meiner Familie und meinem Freund Stefan Zohner, meiner Freundin Annkatrin Erbse allen anderen Freunden für den besonders starken emotionalen Rückhalt über die gesamte Dauer meines Studiums.

Yvonne Katemann

Freising, 18.06.2020