Optimization of organic potato production

Influence of agronomical measures on yield and quality of table potatoes and processing potatoes

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“The fact is, that to do anything in the world worth doing,
we must not stand back shivering and thinking of the cold and danger,
but jump in and scramble through as well as we can.”

- Robert Cushing

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Summary

The cultivation of potatoes in organic farming is subject to high demands at the marketing stage with regard to optical and sensory quality. To be commercially profitable, required quality factors as well as a sufficient yield must be achieved. It was examined whether different agronomic measures affect the yield and quality of organically grown potatoes. This thesis includes a state-wide German field study on organic table potato cultivation in the years 2007-2009 (chapter 2), a field experiment on cultivation of organic processing potatoes in the years 2002/03 and 2003/04 (chapter 3) and a literature study on the subject of volatile compounds in raw, boiled and baked potatoes (chapter 4).

In chapter 2 of this work the results of studies concerning the effects of different cultivar, site properties, agronomic measures and weather and growing conditions on quality of potatoes in the skin were presented and discussed. Besides the measurement of nitrate and starch concentrations a sensory analysis was performed by a trained sensory panel. Peeling ability, flesh colour, mealiness as well as sweet and bitter notes were evaluated.

- Total tuber yield and the internal quality characteristics were primarily influenced by the prevailing weather conditions. The infestation of late blight (*P. infestans*) resulted in lower yields (162 vs. 337 dt ha^{-1}) and starch concentrations (9.6 vs. 12.4 % in FW) and relatively high nitrate levels (121 vs. 104 mg kg^{-1} FW) compared to *P. infestans*-poor years. Tubers from infested fields were rated particularly bitter and less sweet in taste by the panel.
- Total tuber yield, starch and nitrate concentrations correlated significantly with the length of the growing season (r = 0.65, r = 0.30 and r = -0.25, respectively). Higher average temperatures had a significantly positive effect on tuber sweetness (r = 0.27). On irrigated fields an average yield increase of about 25 % compared to non-irrigated fields was obtained (309 and 247 dt ha^{-1}, respectively). Organic N fertilization led to a significant decrease in starch concentrations. Agronomic measures had no influence on the sensory parameters.
- Significant relationship between nitrate and starch concentrations and sensory properties were found: starch is positively correlated with peeling ability (r = 0.60), mealiness (r = 0.61) and a sweet note (r = 0.53); nitrate shows a positive correlation with bitterness (r =0.46) and correlates negatively with starch (r = -0.51), peeling ability (r = -0.34) and mealiness (r = -0.33). The yellow flesh colour correlates negatively with starch (r = -0.60), peeling ability (r= -0.43), mealiness (r = -0.46) and sweet note (r = -0.37) and correlates positively with bitterness (r = 0.50).

In chapter 3 it was examined to what extent different defoliation systems as cutting, mulching and a combination of cutting and mulching of the pre-crop ryegrass clover, influence tuber yield as well as the quality of organically grown potatoes for industrial processing into French fries and crisps. Pre-crop parameters, ryegrass-clover shoot matter and the yield of potentially harvestable shoot matter of mulched stocks (composed of the single growth), the percentage of clover, the annual N-amount of ryegrass-clover, the organic matter (OM), N-amount as well as the C:N-ratio of ryegrass-clover residues were determined. In the respective subsequent years (2003, 2004) harvested processing potatoes cvs Marlen and Agria total tuber and size-graded yields, dry matter and starch concentrations, levels of reducing sugars, nitrogen and mineral elements (K, Mg, P) were quantified. Significant main results can be summarized as follows:

- The mulching variant resulted, in comparison to the pure and mixed cutting variant, in significantly higher OM (874 vs. 481 and 537 g N m^{-2}, respectively) and N-amounts (22 vs. 14 and 15 g N m^{-2}, respectively) in 2002, which led to significantly higher tuber yields in 2003 (36 vs. 34 and 33 t ha^{-1}, respectively). In 2004, the different defoliation systems showed no significant effect on tuber yield.
- In 2003, cv. Agria (36 t ha^{-1}) had a yield advantage of 12 % compared to cv. Marlen (32 t ha^{-1}). In 2004, no significant cultivar effect occurred.
- Mulching resulted in significantly higher tuber yield fraction in the size-grade 50-60 mm in 2003 (11 t ha^{-1}). Significant interactions between defoliation system and cultivar were observed for tuber yields 40-50 mm in 2004. The required size-grade of >35 mm with a proportion of at least 60 % of tubers >50 mm of the organic French fries industry, was with 52.6 % in 2003 and 56.9 % in 2004 not reached. A superposition of the effect of the defoliation system on tuber yield fraction by early and increased occurrence of *P. infestans* in 2004 has to be considered.
- In both years, mulching resulted in the lowest tuber dry matter concentrations (2003: 26.6 % in FW; 2004: 23.2 % in FM). Due to the early infestation of *P. infestans* and therefore a reduced growing season, lowest dry matter concentrations were measured in 2004. Tubers from the cut-used defoliation systems were characterized by significantly highest starch concentrations, especially in cv. Marlen in 2004 (21.6 % in FW). In 2003, starch concentrations of both cultivars were with 19 % and 22 % above the required maximum thresholds for processing into French fries (14-18 %) and crisps (16-20 %). Here, storage led to a slight change of starch concentrations (Marlen +3 %; Agria -2 %).
- In 2003, the maximum level for reducing sugar concentrations of 1.5 g kg^{-1} FW for processing into crisps and 2.5 g kg^{-1} FW for processing into French fries after harvest (Agria: 0.13 g kg^{-1} FW; Marlen: 0.09 g kg^{-1} FW) and after storage (Agria: 0.29 g kg^{-1}

FW; Marlen: 0.23 g kg^{-1} FW) were not exceeded. In 2004, clearly higher concentrations were measured. Storage led in both years to a significant increase in reducing sugar concentrations. In 2004, after storage reducing sugar concentrations were in tubers from the cut-used variant of the cv. Marlen with 2.1 g kg^{-1} FW above the maximum value for crisps production.

- 1x-mulching resulted in cv. Marlen to significantly highest K concentrations. A significant cultivar effect was found in 2004 for Mg and P concentrations.
- Additional slurry fertilization (75 kg N_t ha^{-1}) led to a decrease of tuber dry matter and starch concentrations and to a significant increase of N and K concentrations in the tubers.

Chapter 4 includes a literature study on quality definition, notably the notion flavour. The main focus lies on the volatile compounds. It’s different development and identification and its relevance for the flavour in raw, boiled and baked potatoes are outlined.

- Flavour is created by aromatic volatile compounds that are biosynthesized in the plant during metabolic processes and further modified by cooking or processing. Especially the thermal reaction products are of decisive importance and responsible for the boiled and baked potato flavour. Important thermally driven reactions include the *Maillard* reaction, Strecker degradation and the thermal and enzymatic degradation of fatty acids.
- Site conditions, fertilization, storage, and processing can alter the genetically determined flavour and affect the sensory quality. There are hardly any findings about the effects of different agronomic measures on the formation and composition of volatile compounds.

Conclusion: The dry matter and starch concentration, the concentration of reducing sugars, the nitrate concentration and the quality of the final product are significantly influenced by the choice of cultivar. In addition, the weather conditions during the growing season, as precipitation, solar radiation and temperature, are responsible for yield and quality formation of table and processing potatoes. The effect of agronomic measures such as fertilization, pre-cropping and its different defoliation (mulching, cutting) was rather small. Significant effects in both field studies were felt as a result of the timing and the intensity of infestation with *Phytophthora infestans*, and thus of the available growth period.

The influence of agronomic measures on the sensory quality of organic potatoes in the skin was possibly compensated by the occurrence of *Phytophthora infestans*. Follow-up investigations on these measures should be conducted, to further improve the quality of organic potatoes and thus meet the consumer’s market demands.

Zusammenfassung

Der Anbau von Kartoffeln im ökologischen Landbau unterliegt hohen Anforderungen bei der Vermarktung im Hinblick auf die optische und sensorische Qualität. Für die betriebswirtschaftliche Rentabilität müssen geforderte Qualitätskriterien erreicht sowie ein ausreichender Ertrag erzielt werden. Es wurde geprüft, inwieweit unterschiedliche agronomische Maßnahmen den Ertrag als auch die Qualität von ökologisch angebauten Kartoffeln beeinflussen. Die Thesis beinhaltet eine bundesweite Feldstudie zum ökologischen Speisekartoffelanbau in den Jahren 2007-2009 (Kapitel 2), einen Feldversuch zum Anbau von ökologisch erzeugten Verarbeitungskartoffeln in den Jahren 2002/03 und 2003/04 (Kapitel 3) sowie eine Literaturstudie zum Thema Aromastoffe in rohen, gekochten und gebackenen Kartoffeln (Kapitel 4).

In Kapitel 2 dieser Arbeit wurden die Ergebnisse von Untersuchungen zur Auswirkung von Sorte, unterschiedlichen Standorteigenschaften, agronomischen Maßnahmen sowie Wachstums- und Witterungsbedingungen auf die Qualität von Pellkartoffeln vorgestellt und diskutiert. Neben der Messung von Nitrat- und Stärkegehalten wurde eine sensorische Analyse von einem geschulten Sensorikpanel durchgeführt. Pellfähigkeit, Fleischfarbe, Mehligkeit sowie Süße- und Bitternoten wurden bewertet.

- Der Ertrag sowie die inneren Qualitätsmerkmale wurden vorrangig beeinflusst durch die vorherrschenden Witterungsbedingungen. Das Auftreten von Krautfäule (*P. infestans*) führte zu geringeren Erträgen (162 zu 337 dt ha^{-1}) und Stärkekonzentrationen (9.6 zu 12.4 % in FM) sowie erhöhten Nitratkonzentrationen (121 zu 104 mg kg^{-1} FM) im Vergleich zu *P. infestans*-armen Jahren. Die Knollen von den befallenen Feldern wurden von dem Sensorikpanel als besonders bitter und weniger süß im Geschmack bewertet.
- Gesamtertrag, Stärke- und Nitratgehalt korrelierten signifikant mit der Länge der Vegetationsperiode (r = 0,65, r = 0,30 beziehungsweise r = -0,25). Höhere Durchschnittstemperaturen wirkten sich signifikant positiv auf die Süßenote der Knollen aus (r = 0,27). Bei zusätzlicher Beregnung wurde ein Mehrertrag von durchschnittlich 25 % gegenüber den nicht beregneten Flächen (309 und 247 dt ha^{-1}) verzeichnet. Organische N-Düngung führte zu einer bedeutenden Abnahme der Stärkekonzentration. Die ackerbaulichen Maßnahmen hatten keinen Einfluss auf die sensorischen Parameter.
- Signifikante Zusammenhänge zwischen Nitrat- bzw. Stärkekonzentrationen und den sensorischen Eigenschaften wurden gefunden: Stärke korreliert positiv mit

Pellfähigkeit (*r* = 0,60), Mehligkeit (*r* = 0,61) und Süßenote (*r* = 0,53); Nitrat zeigt eine positive Korrelation zur Bitternote (*r* = 0,46) und korreliert negativ mit Stärke (*r* = -0,51), Pellfähigkeit (*r* = -0,34) und Mehligkeit (*r* = -0,33). Die gelbe Fleischfarbe korreliert negativ mit Stärke (*r* = -0,60), Pellfähigkeit (*r* = -0,43), Mehligkeit (*r* = -0,46) und Süßenote (*r* = -0,37), und korreliert positiv mit der Bitternote (*r* = 0,50).

In Kapitel 3 wird begrenzt auf einen Standort der Einfluss von unterschiedlichem Bewirtschaftungsmanagement der Vorfrucht Rotkleegras, wie Schnittnutzung, Mulchnutzung und einer kombinierten Nutzungsform aus Schnitt- und Mulchnutzung, auf den Ertrag sowie die Qualität von ökologisch angebauten Kartoffeln für die industrielle Verarbeitung zu Pommes frites und Chips dargestellt. Die Vorfruchtparameter, Rotkleegras-Gesamtertrag bzw. die potenziell erntbare Jahressprossmasse der gemulchten Bestände (zusammengesetzt aus den Einzelaufwüchsen), der Kleeanteil (%), die Jahres-N-Menge des gesamten Kleegrasaufwuchses, die organische Masse und die N-Menge der Ernterückstände, sowie die C:N-Verhältnisse der Ernterückstände wurden bestimmt. Die in jeweiligen Folgejahren (2003; 2004) geernteten Verarbeitungskartoffeln der Sorten Marlen und Agria wurden nach Gesamt- und sortierten Knollenerträgen, Trockenmasse- und Stärkegehalten, Gehalten an reduzierenden Zuckern sowie nach Stickstoff und Mineralstoffen (K, Mg, P) quantifiziert. Wesentliche Ergebnisse lassen sich wie folgt zusammenfassen:

- Die Mulchvariante der Vorfrucht Kleegras resultierte im Vergleich zu der reinen Schnittnutzung und der Kombination aus Schnitt- und Mulchnutzung in 2002 zu einer signifikant höheren Anreicherung von organischer Masse (874 vs. 481 bzw. 537 g N m^{-2}) und damit zu einer höheren N-Nachlieferung (22 vs. 14 bzw. 15 g N m^{-2}), wodurch in 2003 der signifikant höchste Kartoffelertrag (36 vs. 34 bzw. 33 t ha^{-1}) erzielt wurde. In 2004 zeigte das unterschiedliche Nutzungsregime keinen signifikanten Einfluss auf den Kartoffelertrag.
- In 2003 wies die Sorte Agria (36 t ha^{-1}) im Vergleich zur Sorte Marlen (32 t ha^{-1}) einen signifikanten Ertragsvorteil von 12 % auf. In 2004 trat kein signifikanter Sorteneffekt auf.
- Das Mulchen von Kleegras führte bei der Größensortierung 50-60 mm zu den signifikant höchsten Kartoffelerträgen in 2003 (11 t ha^{-1}). Bei der Knollengrößenfraktion 40-50 mm traten in 2004 signifikante Wechselwirkungen bei dem Faktor Nutzungssystem*Sorte auf. Die geforderte Größensortierung >35 mm mit einem 60 %-Anteil von Knollen >50 mm, die an Verarbeitungskartoffeln für die Pommes frites Verarbeitung aus ökologischem Anbau gestellt werden, wurde mit 52,6 % in 2003 und 56,9 % in 2004 nicht erreicht. Eine Überlagerung des

Bewirtschaftungseffektes auf die Größensortierung muss durch das frühzeitige und verstärkte Auftreten von *P. infestans* in 2004 in Betracht gezogen werden.

- In beiden Jahren führte das Mulchen zu den geringsten Trockenmassekonzentrationen in den Knollen (2003: 26,6 % in FM; 2004: 23,2 % in FM), wobei in 2004, bedingt durch das frühe Auftreten von *P. infestans* und einer damit verkürzten Vegetationszeit, geringere Konzentrationen gemessen wurden. In 2004 führte die Schnittnutzung von Kleegras bei Marlen zu den höchsten Stärkekonzentrationen (21,6 % in FM). In 2003 lag die Stärkekonzentration beider Sorten mit 19 und 22 % über den für Pommes frites (14-18 %) und Chips (16-20 %) geforderten Maximalwerten. Die Lagerung führte hier zu einer leichten Veränderung der Stärkekonzentration (Marlen +3 %; Agria -2 %).
- In 2003 wurden die erlaubten Höchstwerte an reduzierenden Zuckern von 1,5 g kg^{-1} FM für die Verarbeitung zu Chips bzw. 2,5 g kg^{-1} FM für die Verarbeitung zu Pommes frites nach der Ernte (Agria: 0,13 g kg^{-1} FM; Marlen: 0,09 g kg^{-1} FM) und nach Lagerung (Agria: 0,29 g kg^{-1} FM; Marlen: 0,23 g kg^{-1} FM) deutlich unterschritten. In 2004 wurden deutlich erhöhte Konzentrationen gemessen. Die Lagerung führte in beiden Jahren zu einem signifikanten Anstieg an reduzierenden Zuckern. In 2004 lag nach der Lagerung der Gehalt an reduzierenden Zuckern in Knollen der Sorte Marlen bei Variante Schnittnutzung mit 2,1 g kg^{-1} FM deutlich über den Grenzwerten zur Chips-Herstellung.
- Das 1x Mulchen des Kleegrases in 2004 führte bei Marlen zu den signifikant höchsten K-Konzentrationen. Ein signifikanter Sorteneffekt trat in 2004 bei den Mg-und P-Konzentrationen auf.
- Die zusätzliche Gülledüngung (75 kg N_t ha^{-1}) führte zur Abnahme von Trockenmasse- und Stärkekonzentrationen und zu einem signifikanten Anstieg der N- und K-Konzentrationen.

Das Kapitel 4 umfasst eine Literaturstudie zum Qualitätsbegriff, insbesondere über die Aromastoffe bzw. dem Begriff „Flavour“. Hauptaugenmerk gilt den flüchtigen Verbindungen, deren Entstehungswege aufgezeigt, ihre Verteilung sowie ihre Bedeutung für das Aroma roher, gekochter und gebackener Kartoffeln ausführlich dargestellt werden.

- Flüchtige Aromastoffe entstehen durch metabolische Prozesse in der Knolle bzw. durch den eigentlichen Verarbeitungsprozess. Für das Aroma gekochter bzw. gebackener Kartoffeln sind insbesondere die thermischen Reaktionsprodukte von ausschlaggebender Bedeutung. Wichtige Reaktionen sind die *Maillard*-Reaktion, die Strecker-Degradation und der thermische Abbau von Fettsäuren.
- Standort, Düngung, Lagerung, sowie die Verarbeitung können das genetisch festgelegte Aroma verändern und damit die sensorische Qualität beeinflussen. Die Aus-

wirkungen unterschiedlicher Bewirtschaftungsmaßnahmen auf die Entstehung und die Zusammensetzung flüchtiger Verbindungen ist bislang wenig untersucht.

Fazit: Der Trockenmasse- und Stärkegehalt, der Gehalt an reduzierenden Zuckern, der Nitratgehalt sowie die Qualität des Endproduktes werden maßgeblich durch die Sortenwahl beeinflusst. Darüber hinaus sind die Witterungsbedingungen während der Vegetationsperiode, wie Niederschlagsmenge, Sonneneinstrahlung und Temperatur, für die Ertrags- und Qualitätsbildung der Speise- und Verarbeitungskartoffeln verantwortlich. Acker- und pflanzenbauliche Maßnahmen, wie Düngung, Wahl und Nutzungsart der Vorfrucht, zeigten in den Untersuchungen einen eher geringen Einfluss. Deutliche Effekte gingen in beiden Feldstudien vom Zeitpunkt und der Stärke des Befalls mit *P. infestans* aus und damit von der zur Verfügung stehenden Wachstumsphase. Da die Pilzinfektion möglicherweise den Einfluss der acker- und pflanzenbaulichen Maßnahmen auf die sensorische Qualität von Bio-Kartoffeln kompensiert, sollten weitere Untersuchungen durchgeführt werden. Durch dieses Wissen könnte der ökologische Kartoffelanbau weiter optimiert werden, um so die Qualität von Bio-Kartoffeln weiter zu verbessern und damit den Verbraucherwünschen gerecht zu werden.

1 General introduction

Potatoes (*Solanum tuberosum* L.) are the world’s most popular vegetable. Annually world production is around 300 million tons and areas planted cover more than 18 million hectares (Cipotato 2008). The secret of the potato’s success is its great diversity in colours, textures and tastes (FAO 2008) and its varied preparation possibilities, including simple boiling, baking, deep fat frying and dehydration. The demand for organically grown potatoes has gradually increased worldwide. Besides health concerns, in particular, better texture and taste frequently motivates consumers to purchase organic products (Bollinger 2001). 43 % of organic consumers state better taste as a major reason for purchasing (Heaton 2001). The acreage of organic potatoes has increased in Germany significantly since the late 1990s from 4.750 ha to 8.350 ha. In 2009, already 7.3 % of the German table potato cultivation area was used for the production of organic potatoes (AMI 2010). This development has been encouraged by the growing demand for organic potatoes since 2000 when discounters entered the market with first test sales. This move led to dramatic changes in distribution channels, so that in 2011 almost 60 % of organic potatoes are sold through discounters or nearly 80 % by food retailers (Böhm et al. 2011). Processing is a segment of the organic food industry that looks set to grow significantly over the next few years. Organic convenience foods are a relatively new concept in many of the more mature markets, such as the United States and Britain, where the organic processing sectors are the fastest growing (Smithson 2007). It is significant that more and more major food manufacturers and mainstream food brands, such as McCain, the German company Funny Frisch or the supermarket chain REWE, with its own store brand, are now marketing organic chips and French fries. Due to increasing demand for convenience-products, organic potato cultivation for industrial processing into French fries or potato crisps will be a new source of income for German growers (Kuhnert et al. 2004). Different expectations are placed on the product depending on the preparation method. Consumer demand for organic table potatoes with above-average quality attributes has increased (Schulz 1998), whereby consumer buying behaviour is less influenced by external quality than by the taste and the health qualities of a food (Meier-Ploeger 1988). The quality requirements on raw processing potatoes are high and differ from those for table potatoes. The potatoes need to have good storage stability, low damage sensitivity, as well as a high portion of larger tubers for French fries and crisps (Schuhmann 1999; Böhm 2003; Haase et al. 2007b). Furthermore, ranges and thresholds for starch, tuber dry matter (DM), as well as for the concentration of reducing sugars (glucose and fructose) of tuber fresh matter (Putz and Lindhauer 1994; Schuhmann 1999)

are required. In addition, it has been found that nitrogen and mineral substances, potassium (K), magnesium (Mg) and phosphor (P) influence the sensory quality characteristics of the processed products (Pawelzik 2000).
Thus, for organic table potatoes as well as for potatoes to be processed into French fries or crisps, both, high tuber quality and above-average yields are essential factors for the commercial profit of the growers. To meet these market demands, a continuous optimization of crop management is required by farmers. It is known, that the choice of cultivar, degree of maturity, method of cultivation, locality and soil, seasonal variations, temperature during growth (Heinze et al. 1955) and length of growth period affect tuber yield and quality formation (Hospers-Brands et al. 2008). Finckh et al. (2006) stated that the nitrogen supply and the occurrence of late blight, caused by *Phytophthora infestans*, are the main factors generally limiting tuber yield and quality formation in organic potato cropping. High nitrogen contents results in a decrease of starch (Hunnius 1972) and reducing sugar concentrations (Kolbe 1990) and leads to a bitter taste in the tubers (Cieslik 1997). N nutrition in organic potato cropping can be reached either by cultivation of preceding crops, such as legumes (Finckh et al. 2006; Haase et al. 2007a), and/or by application of organic fertilizer (Haase et al. 2007b). Tuber nitrogen concentration is not only influenced by N fertilization, but also depends on cultivar and the degree of maturity (Haase et al. 2007b).

The aim of the present thesis is to evaluate different agronomic measures influencing yield and quality formation of organic table potatoes and of organic potatoes for processing. The thesis includes one field experiment, one field study as well as a literature study. The first key subject of the present thesis was working out factors, in a part of a field study, that are essential for the formation of the external, internal as well as the sensory quality. Besides to the influence of cultivar, the cropping and management factors as well as the growth and weather conditions were evaluated. To this, nitrate and starch concentrations of raw potatoes, as well as on the quality of cooked potatoes in the skin were determined. A professional sensory panel scored the most important sensory attributes for consumers: peeling ability, flesh colour, mealiness, sweetness and bitterness. The second key subject was the effect of different defoliation systems of ryegrass-clover mixtures and an additional fertilization on yield as well as on selected external and internal quality attributes of organically grown potatoes for processing into French fries or crisps. Furthermore, the influence of a 4-month storage period on selected internal quality parameters was investigated. At the end of the thesis the formation and the importance of the various desirable and rather less desirable volatile and non-volatile compounds, which occur in raw, boiled and in processed potatoes, like French fries or crisps, were presented and discussed and their impact on flavour documented. In addition, in the context of this literature study, the impact of different cultivation methods, fertilizer treatments, cultivars, storage and types of preparation, on the sensory properties, such as taste, was evaluated.

The thesis is divided into five chapters. Chapters 2-4 comprise three manuscripts which are published or are submitted to international peer-reviewed journals. Chapter 2 focuses on cooking quality and compositional factors of organic potatoes (*Solanum tuberosum* L.) of different cultivars under different growing conditions (*Organic Agriculture 2012, submitted*). Chapter 3 contains a study on the effect of different defoliation systems of ryegrass-clover on the yield and selected quality parameters of organic potatoes (*Solanum tuberosum* L.) for industrial processing at harvest and after storage (*Potato Research 2012, submitted*). Chapter 4 deals with the influence of volatile compounds of the flavour of raw, boiled and baked potatoes and the impact of agricultural measures on the volatile components (*Landbauforschung Volkenrode 2009, 59 (4), 309 – 337*). The final chapter discusses the main and new achievements of the three studies.

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2 Cooking quality and compositional factors of organic potatoes (*Solanum tuberosum* L.) of different cultivars under different growing conditions

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Abstract

The aim of the study was to investigate if cultivars, different growing conditions such as weather and soil properties or agronomic measures such as seed quality, preceding crops, application of organic fertilizer and irrigation influence the nitrate and starch concentrations of raw potatoes and the cooking quality of potatoes in the skin. Cultivation and quality data were collected for three waxy cultivars (cvs Princess, Nicola, Ditta) from 183 organically managed potato fields in Northern and Southern Germany from 2007-2009. A professional sensory panel scored peeling ability, flesh colour, mealiness, sweetness and bitterness by means of consensus profiling. Differences in nitrate and starch concentrations were often attributed to weather conditions during the growth period and to the occurrence of *P. infestans*. The sensory analysis showed different sensory profiles for the three cultivars from the different years and regions. Year*region interactions were significant for all traits except for peeling ability. A significant interaction year*cultivar was only found for yellowness, mealiness and sweetness. Early haulm dying in Northern Germany in 2007 resulted in a more pronounced taste of bitterness, which was associated with lower starch and higher nitrate levels. The following influences of cultivation methods on yield and chemical components (starch, nitrate) were found: the additional irrigation led to a significant average yield increase of about 25% compared to non-irrigated fields (309 and 247 dt ha^{-1}). The application of nitrogen-containing organic commercial fertilizers resulted in a decrease in starch concentration. There was no significant relationship between cultivation data and sensory attributes. However, starch concentration was positively correlated with peeling ability (r = 0.60), mealiness (r = 0.61) and sweetness (r = 0.53). Nitrate concentration was positively correlated with bitterness (r = 0.46) and negatively correlated with starch (r = -0.51), peeling ability (r = -0.34) and the mealiness (r = -0.33) of cooked potatoes. As the sensory quality of cooked potatoes in the skin produced under different growing conditions and agronomic measures had not been addressed previously, this study revealed interesting results.

Keywords: Organic farming; Potato; Starch; Nitrate; Sensory quality; Taste; Texture

2.1 Introduction

Table potato quality is characterised by external quality, cooking (internal) quality and biological value. The external quality includes tuber size, shape, colour, wholeness and health. The cooking quality comprises flesh colour, texture or mealiness, flavour and tendency to discolouration. The biological value is determined according to its chemical composition (Varis 1970). Consumer demand for organic table potatoes with above-average quality attributes has increased (Schulz 1998). In particular, a better texture and taste are consumer motives for the purchase of organic products (Bollinger 2001; Heaton 2001).

Organic potatoes are subject to the same requirements on sensory qualities as conventional potatoes, but the production costs for organic potatoes are higher and the yields lower (Yue et al. 2010). According to the study of Pimentel (1993) yield of organic potatoes was with 150 dt ha^{-1} 50 % lower and the cost of production 50 % higher than conventional potato production. An evaluation of agricultural reports in Germany also showed that the yield level of organically grown potatoes is only half that of the conventional reference group (Böhm et al. 2011a). Thus, both high tuber qualities as well as above-average yields are important factors for growers (Arvanitoyannis et al. 2008a).

Several groups have investigated the effect of different growing conditions on potato dry matter and starch concentration (Kolbe 1990; Neuhoff et al. 1999; Neuhoff and Köpke 2002; Haase et al. 2007) and the effects of organic versus conventional systems on sensory attributes (Hansen 1981; Woese et al. 1997; Hajslova et al. 2005; Wszelaki et al. 2005). Thybo et al. (2001) analysed the sensory quality of cooked potatoes fertilized with cattle slurry and cattle deep litter manure. They found a significant decrease of starch concentrations and an increase of N concentrations after slurry fertilization. Potatoes fertilized with slurry were slightly moister and less yellow than potatoes fertilized with deep litter manure. Varis (1970), Arvanitoyannis et al. (2008b), Jansky (2008), Pevicharova and Nacheve (2009) and Seefeldt (2010) investigated effects influencing the quality and sensory attributes of differently prepared potatoes (cooked, oven-baked and mashed) grown on different conventional fields. According to Seefeldt (2010) potatoes grown on a sandy soil site had a higher content of dry matter compared to those grown at a loamy location. Varis (1970) found among other things that a prolonged rise in temperature had an increasing influence on the mealiness of the tuber flesh.

However, the relationships between the texture and taste of cooked potatoes, as well as starch and nitrate concentrations of fresh tubers according to cultivar type and various growing conditions, remain unclear. Further to our knowledge, no study has yet investigated such associations in organic table potatoes in the skin.

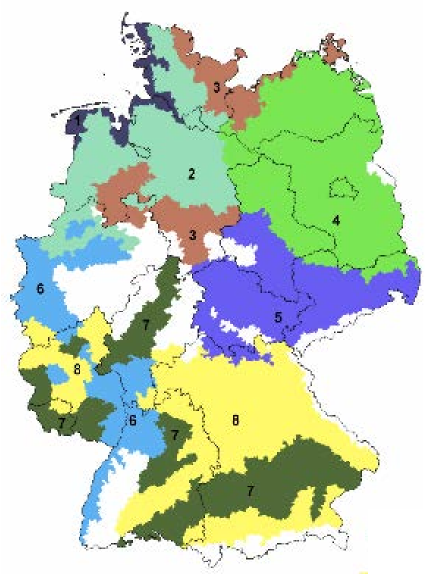
New approaches to improve the quality of organic potatoes are important for increasing sales. This includes optimization of raw material quality. In order to improve the quality of cooked potatoes, the relative contributions of cultivar and production environment need to be fully understood. Cultivar, degree of maturity, method of cultivation, amount and kind of fertilizers, site and soil, seasonal variations, temperature during the growing period (Heinze et al. 1955) as well as length of growing period affect chemical compositions (Hospers-Brands et al. 2008). Therefore the quantification of these factors on raw material is needed to improve the quality of the cooked potatoes.

Thus, the aim of the present study performed in three subsequent years (2007-2009) and two different regions in Germany was to investigate the relative contributions of cultivars (cvs Princess, Nicola and Ditta) and selected agronomic measures on yield, starch and nitrate concentrations and sensory quality (peeling ability, yellowness, mealiness, sweetness, bitterness) of cooking quality of organic potatoes in the skin.

2.2 Material and Methods

2.2.1 Experimental sites and conditions

Cultivation and quality data of organic potato production were collected between 2007 and 2009 (Table 2.1). Participating organic farms were located in Northern and Southern Germany. The regional assignment of the growing areas was carried out according to Graf et al. (2009), who defined crop-specific areas to guarantee the accuracy and representativeness of experimental results, used to derive practically oriented, regional advisory recommendations. The crop-specific areas (1-8) for potatoes are displaced in the following figure (Fig. 2.1).



1	marsh
2	sandy soil northwest
3	loam soil north
4	diluvial sites East Germany
5	loess and weathered sites Central/East Germany
6	altitude southwest/loess and loamy sites west
7	middle altitude south
8	high altitude south

Figure 2.1: Potato specific growing areas (Graf et al. 2009)

In the present study farms were located in areas 2, 3, 7 and 8. Farms from site numbers 2 and 3 were assigned to Northern Germany (NG) and farms from site numbers 7 and 8 were assigned to Southern Germany (SG). The farms from different climatic potato-growing sites differed in soil textures (light, medium and heavy soil) and in their management systems (crop rotation, seed preparation, farms without livestock, mixed farms with livestock, farms with and without irrigation) (Table 2.1, also Böhm et al. 2011b). In SG the acreage of the farms included in the study ranged between 10 and 40 ha. Many farms were characterized by a high degree of specialisation in potato production; these farms were often without livestock. The size of the participating farms in NG varied between 40 and 150 ha. Potato cultivation was the main pillar for the farms in this region. Additional livestock farming with dairy cattle or poultry were found. In NG the majority of farms irrigated their fields with a sprinkler irrigation system (Table 2.1). All relevant cultivation and potato quality data were collected.

Table 2.1: Characterization of farms in Northern and Southern Germany in the years 2007-2009. Number of farms (n) with selected parameters

Parameter	Northern Germany *n* = 105	Southern Germany *n* = 78
Cultivars		
Princess	48	16
Ditta	22	41
Nicola	35	21
Soil texture		
light	52	22
medium	35	45
heavy	18	11
Seed stock		
certified seed stock	81	52
home saved seed stock	23	25
Seed treatment		
copper dressing	29	4
FZB	6	24
Rhizovital	4	20
without	66	29
Seed processing		
presprouted	18	13
stimulated	86	65
Preceding crop combination		
grass clover – grain	2	9
vegetable – grain	16	1
grain – grass clover	6	26
grain – clover	9	5
grain – vegetables	7	3
grain - grain	49	9
other	16	25
Farm fertilizer		
biogas slurry	13	16
poultry manure	33	12
cattle manure	9	0
without	50	50
Organic commercial fertilizer		
hair flour pellets	32	1
Bioilsa	0	21
Potato Protein Liquid (PPL)	9	1
without	64	55
Irrigation		
with	70	10
without	35	68

2.2.2 Measurements and observations

Daily weather data were obtained from the weather stations nearest to the participating farms. Two exemplary weather stations were chosen for the description of the weather data in Northern and Southern Germany. The weather station in NG was located in Soltau (52°96’N; 9°8’E)/Luneburg Heath, a representative potato growing area in Lower

Saxony. In SG the weather station was located close to Ingolstadt (48°7'N; 11°5'E), the main potato cultivation area in Bavaria. Average weather conditions differed between Northern and Southern Germany each year. Precipitation amounts were in 2007 with 1089 mm in NG and 843 mm in SG the highest in comparison to the years 2008 and 2009 (*Deutscher Wetterdienst* (DWD); see Table 2.2). With 770 mm in 2009 in NG and 701 mm in 2008 in SG lowest precipitation amounts were measured. In the high-rainfall year 2007, significantly highest annual air temperatures were measured in both sites (10.1°C in NG; 9.7°C in SG). SG showed in all trial years more hours of sunshine compared to NG; this was particular pronounced in 2007 (162 h).

The witnessed above-average rainfall amounts in May to July in NG in 2007 caused an area-wide infestation with *Phytophthora infestans* with a primary infection of the stems. Although precipitation was also high in SG (Table 2.2), the distribution of rainfall led to less widespread primary infection with *P. infestans*. In 2009, however, high precipitation, especially in May and June (see Table 2.2) resulted in an early and rapid infestation with *P. infestans* in this region. In contrast, May and June were very dry in NG and late blight occurred only to a limited extent. The weather conditions did not differ notably from the norm in either region in 2008 as compared with 2007 and 2009. In SG there were isolated cases of infection with *P. infestans*. The start of *P. infestans*, as well as the beginning of haulm dying, was documented by the farmers.

2.2.3 Samplings and analysis

Seed tubers from the farms were planted at different times between the ends of March and mid-May, harvested in August to September and transported to the cold storage of the sensory laboratory, where they were stored until analysis. The potatoes were stored in the dark at 40 % relative humidity at 4°C. The planting and harvest dates as well as the yield level were documented by every farmer.

Nitrate concentrations of fresh tubers were determined using the Nitracheck-Reflectometer (Nitracheck 404, (U.K.)). A sample was taken from each of 30 tubers. Sample pools were juiced with a household juice extractor (Frutti Pro, Moulinex, (F)). Concentrations of nitrate in the tubers were determined using nitrate test strips (Merckoquant, Range 10-500 mg/l NO_3, Merck, (D)) according to Nitsch (2003). The underwater weight of the potatoes was determined (Brückmann 1876) and starch concentrations estimated according to the regression equation of Putz (1989). After cleaning the samples with tap water, the weight of wet potato tubers in water was measured with a starch-balance (DE 24K2N, Kern & Sohn, (D)).

Sensory analyses were only conducted with tubers from the 35-60 mm size graded range. About thirty batches of each cultivar were analysed per harvest year. The tubers were cleaned manually, and damaged or green tubers were discarded. Potatoes were cooked unpeeled in salt-free boiling tap water for 20-25 minutes until they reached a core temperature of 75°C. The potatoes were kept in a thermos dish until served to assessors of the sensory panel. They were served blind with a three-digit code. Six samples were subsequently served to each assessor of the sensory panel, representing three replicate measurements. The peeling ability was evaluated and the appearance, taste and mouth sensation/consistency of the peeled potato were measured.

Sensory profiling analyses were performed in a sensory evaluation laboratory according to the consensus-profile (DIN 10967-2) (Anonymous 2000). The panel was composed of nine trained assessors from age 30 - 62 years. All panellists were tested for their sensory ability (basic taste, odour detection and colour vision) as well as ability to communicate sensory descriptions of products as recommended in DIN 10961 (Anonymous 1996b). A sensory training was performed before the sensory analysis. First, the panellists developed sensory attributes for appearance, texture and taste according to DIN 10964 (Anonymous 1996a), which were essential for the characterisation and differentiation of the sensory profiles of the analysed potato cultivars. Second, the samples were assessed at individual speed on an unstructured scale with an intensity rating ranging from low (0 %) to high intensity (100 %) for the peeling ability and each attribute (Table 2.3). The panel leader calculated the intensity for the attributes as a consensus value. Based on a list of attributes covering appearance properties (peeling ability, yellowness inside), texture properties (mealiness), and taste properties (sweetness, bitterness) the panel discussed and agreed on a consensus.

Table 2.2: Monthly mean air temperature (°C), sum of precipitation (mm) and mean hours of sunshine (h) at two experimental sites in Northern and Southern Germany during the three consecutive years (2007-2009) according to *Deutscher Wetterdienst* (DWD)

Northern Germany										**Southern Germany**								
Year	**2007**			**2008**			**2009**			**2007**			**2008**			**2009**		
	°C	**mm**	**h**	**°C**	**mm**	**h**	**°C**	**mm**	**h**	**°C**	**mm**	**h**	**°C**	**mm**	**h**	**°C**	**mm**	**h**
Jan	5.2	158	35	4.7	137	22	-0.5	38	51	4.2	48	56	2.3	47	84	-3.8	25	84
Feb	3.6	80	31	4.1	42	93	1.5	67	36	4.0	58	103	3.0	27	160	-0.8	37	58
Mar	6.9	88	165	4.1	107	102	4.9	81	96	5.6	38	174	4.3	63	124	3.7	68	68
Apr	11.7	7	244	7.6	44	133	12.6	19	276	12.1	13	324	8.3	92	139	11.8	25	237
May	13.8	130	221	14.6	19	317	13.4	37	257	14.7	157	241	14.9	47	253	14.3	109	214
Jun	17.7	79	180	16.6	40	254	14.3	45	201	17.9	102	233	17.7	99	214	15.6	106	204
Jul	16.9	147	175	18.3	108	201	17.9	109	211	18.0	123	238	18.0	100	225	18.1	124	210
Aug	16.8	68	174	17.0	101	155	18.3	41	233	17.1	92	195	17.8	67	220	19.1	40	251
Sep	13.2	96	124	13.1	39	144	14.6	29	170	12.1	84	145	12.1	47	117	15.1	29	179
Oct	8.5	55	108	9.5	93	144	7.9	119	84	7.9	15	127	8.7	40	103	8.2	58	88
Nov	4.7	101	51	5.6	48	30	8.3	115	23	2.1	72	52	3.9	35	70	5.9	52	79
Dec	2.6	81	27	2.1	20	32	0.4	72	39	0.3	42	51	0.5	37	64	-0.1	77	44
Mean	10.1		128	9.8		135	9.5		140	9.7		162	9.3		148	8.9		143
Sum		1089			769			770			843			701			752	
Mean May-Aug[1]	15.4	86	199	14.8	56	212	15.3	50	236	16.0	97	246	15.3	81	210	15.8	81	223

Northern Germany (NG) = Soltau (52°96’N; 9°8’E), Southern Germany (SG) = close to Ingolstadt (48°7’N; 11°5’E)

[1] time intervall of *P. infestans* infestation

Table 2.3: The sensory attributes used to describe the sensory quality of organic cooked potatoes (Mahnke-Plesker et al. 2011)

Property	Attribute	Description	Scale points
Appearance outside	Peeling ability	0 %: skin have to cut 50 %: normal, middle-size peeling slice 100 %: two peeling slices	Bad - good
Appearance inside	Yellow	Colour scale 100 %: lemon yellow	Light - strong
Texture	Mealiness	Dry, brittle 75 %: very mealy	Not at all – very strong
Taste	Sweetness	Mashed potato intensity	Not at all – very strong
Taste	Bitterness	Mashed potato intensity	Not at all – very strong

2.2.4 Data analysis

The complete data set was analysed using the software package SAS 9.2 (SAS Institute 2010) and significance was set at $\rho<0.05$. The number of observations was counted with the PROC MEANS procedure. Cultivation parameters for which the number of observations was ≤10 were not included in the statistical analysis. The number of observations was n = 183. Analysis of variance was calculated with the procedure MIXED. Denominator degrees of freedom were approximated by the Kenward-Roger method (Kenward and Roger 1997). Residuals were checked for normal (Gaussian) distribution and homogeneity of variance with PROC UNIVARIATE. If necessary, data were log-, square-root- or arcsinus-transformed and subjected to analysis of variance. LSMEANS and their associated 95 % confidence limits were transformed back to the original scale. Where a significant main effect was observed, *post hoc* between-group differences were assessed by Bonferroni-adjusted pair-wise comparison. A further correlation analysis between variables and independent variables was tested with PROC CORR with the Spearman rank-order correlation. PROC CORR computes the Spearman correlation by ranking the data the coefficients based on the ranks of the variables (SAS Institute 2010). In addition, the 95 %-confidence interval were calculated with focus on lower interval limit >=0.1. At n = 183 the lower limit of the confidence interval of ≥ 0.1 was at r ≥ 0.242, indicated by ***. The value of the coefficient and the strength of the correlation were interpreted in accordance to the standards of Brosius (1998) (Table 2.4).

Table 2.4: Value of the coefficient and the strength of the correlation (Brosius 1998)

Value of Coefficient	Possible Interpretation
0	no correlation
above 0 - 0.2	very weak correlation
0.2 - 0.4	weak correlation
0.4 – 0.6	average correlation
0.6 – 0.8	strong correlation
0.8 – under 1.0	very strong correlation
1.0	perfect correlation

2.3 Results

The effect of three waxy cultivar types grown on organically managed potato fields in Northern and Southern Germany in 2007 – 2009 under different agronomic measures as well as growing conditions on sensory quality of cooked potatoes in the skin was investigated. There were significant effects ($\rho<0.05$) of cultivar type for nearly every trait except yield. Interactions of year*cultivar were found for yellowness, mealiness and sweetness (Table 2.5). However, none of the three tested cultivars showed any significant response to the region for the examined characteristics. In contrast, with the exception of peeling ability, there were significant year effects, which were expressed as year*region interactions (Table 2.5). 3-way interactions were not ascertained. Table 2.6 shows means and significances from ANOVAs of the different parameters. Table 2.7 and 2.8 list the correlation coefficients between the agronomic measurements and yield, as well as chemical parameters of raw tubers, and between the agronomic measurements and the sensory parameters of cooked potatoes in the skin.

2.3.1 Tuber Yield

The tuber yield was significantly affected by a year*region interaction (Table 2.5). A cultivar-effect was not observed. In NG yields were significant higher in 2008 (355 dt ha^{-1}) and in 2009 (320 dt ha^{-1}) compared to 2007 (162 dt ha^{-1}; Table 2.6). In contrast, in SG yield was significant higher in 2007 (291 dt ha^{-1}) compared to 2008 (229 dt ha^{-1}), while the yield in 2009 (240 dt ha^{-1}) did not significantly differ from the other two years. Thus, the yield was in 2007 in SG significant higher than in NG, while in 2008 and 2009 yield was significant higher in NG than in SG. Interactions between agronomic measures and yield were found on the one hand for the irrigation, which was weak positively correlated (r = 0.38). On the other hand tuber yield was strongly and positively correlated (r = 0.65) with the time interval between planting and infestation with *P. infestans* (Table 2.7). Furthermore, the weather conditions had an influence on yield, which was weak positive correlated with the sum of global radiation (r = 0.32) as well as weak negatively correlated with the sum of precipitation (r = -0.35).

2.3.2 Nitrate concentrations

There was a significant main effect of cultivar and a year*region interaction effect on nitrate concentrations in tubers (Table 2.5). Nitrate concentrations were significantly higher in cv. Princess (155 mg kg^{-1}) than in cv. Ditta and cv. Nicola (both 97 mg kg^{-1}) (Table 2.6). In 2007 and 2009, there were no significant differences between Northern and Southern Germany concerning the nitrate concentrations, while in 2008 the nitrate concentrations in SG were with 155 mg kg^{-1} significantly higher compared to NG with 109 mg kg^{-1} (Table 2.6). In NG nitrate concentrations were on a similar level in all the three years, while in SG in 2008 significantly higher nitrate concentrations were presented compared to 2007 and 2009 (Table 2.6).

The correlation analysis showed a weak negative relationship between time interval between planting and beginning of *P. infestans* and nitrate concentration (r = -0.25; Table 2.7).

2.3.3 Starch Concentrations

Cultivar and a year*region interaction had a significantly effect on starch concentrations (Table 2.5). Significant highest starch concentrations were measured in cv. Nicola (13 % in FW) followed by cv. Ditta (12 % in FW) and cv. Princess (9.8 % in FW) (Table 2.6). While in 2008 there were no significant differences concerning the starch concentrations in Northern and Southern Germany (12.0 and 11.7 % in FW), in 2007 starch concentrations in tubers from SG were significantly higher (12.9 % in FW) and, in 2009 significantly lower compared to NG (12.7 % in FW). In NG significantly higher starch concentrations were identified in 2008 and 2009 (12.9 % and 12.7 % in FW, respectively) compared to 2007 (10 % in FW). In contrast, in SG there were significantly higher starch concentrations in tubers from harvest 2007 (13 %), while in 2008 and 2009 no significant differences in starch concentrations were ascertained (both 11.7 % in FW).

There were significantly weak positive correlations between organic commercial fertilizer and starch (r = 0.26), between the time interval between planting and beginning of *P. infestans* and starch concentration (r = 0.30) (Table 2.7). Starch concentrations were inversely related to nitrate concentrations (r = -0.51; Table 2.8).

2.3.4 Sensory Attributes

2.3.4.1 Peeling ability

The peeling ability was significantly affected by the main factors year and cultivar (Table 2.5). Tubers from harvest 2008 demonstrated with 57.3 % the best peeling ability, which was significantly better than 2007 (49.6 %) (Table 2.6). The cvs Ditta and Nicola showed with 61 and 60 % the best peeling ability compared to cv. Princess with 43 %.

No interactions between agronomic measures and peeling ability were found, but the sensory panel scored for peeling ability weak negative correlations with nitrate concentrations (r = -0.34) and positive correlations with starch concentrations (r = 0.60) (Table 2.8).

2.3.4.2 Yellowness

The flesh colour yellowness was significantly affected by the two 2-way interactions year*region and year*cultivar (Table 2.5). In 2007, potatoes from NG had with 36 % the significant highest yellow intensity compared to tubers from SG with 29 %, while in 2008 tubers from SG had the significant highest yellow intensity (27 %) compared to tubers from NG (21 %) (Table 2.6). In 2009, there were no significant differences in flesh colour between the two regions. In 2007, tubers from NG showed a significantly higher yellow intensity (36 %) compared to tubers harvested in 2008 (21%) and 2009 (25 %). No significant differences concerning yellowness were found in all the three years in SG.

In all three years cv. Princess had a significantly more intensive flesh colour compared to cvs Ditta and Nicola. Cv. Ditta showed in all three years the second highest yellowing, although only in the years 2007 and 2009 it was significantly higher than the yellowing of cv. Nicola (Table 2.6). While the yellow colour of cv. Nicola was in all three years at a low but comparable level, in 2007 cvs Princess and Ditta revealed a stronger yellow colour as in 2008 and 2009, which, with the exception of cv. Ditta in 2009, was significant (Table 2.6).

No correlations between flesh colour and management parameters, but correlations to the chemical compounds were found: strong correlated to the starch concentration (r = -0.60, Table 2.8), weak correlated to the nitrate concentration (r = 0.28, Table 2.8). Furthermore, there was an negative correlation between flesh colour and peeling ability (r = -0.43, Table 2.8).

2.3.4.3 Mealiness

The mealiness of potatoes was significantly affected by two 2-way interactions, year*region and year*cultivar (Table 2.5). While in 2007, tubers from SG were significant mealier (22 %) compared to the tubers from NG (8.5 %), the effect was reversed in 2008 (16.3 vs. 11.0 %) and, in 2009 no differences were observed (Table 2.6). In NG the mealiness intensity was on a comparable level in the years 2007 and 2009 (9 % resp. 10 %), but significantly lower compared to 2008 (16 %). In contrast, in SG significant differences were indicated from year to year, i.e. the tubers harvested in 2007 were significantly the mealiest (22 %), followed by tubers from harvest 2008 (11 %), which were significantly different to the tubers of 2009 (7 %).

In all three years cv. Nicola showed the most mealiness, which in 2007 with 25 % was significantly higher compared to cv. Princess with 11 % and cv. Ditta with 10%. In 2008 and 2009, it was only significantly higher compared to the cv. Princess. Except for 2008, the cvs Princess and Ditta were on a comparable level in the classification of mealiness.

The mealiness of cv. Princess was on a comparable level in 2007 and 2008 (11 and 8 %, respectively) as well as in 2008 and 2009 (8 and 5 %, respectively), but significant different between the years 2007 and 2009 (5 and 15 %, respectively). Cv. Ditta showed the significant highest intensity of mealiness in 2008 (15 %), while in 2007 and 2009, it was on a comparable level (10 and 9 %, respectively). Cv.

Nicola showed significant differences between all the three years with the highest intensity of mealiness in 2007, followed by an averaged in 2008 and the lowest in 2009.

No correlations between mealiness and agronomic measures were found. Mealiness correlated significantly strong with starch concentration (*r* = 0.61; Table 2.8) and inversely weak with nitrate concentrations (*r* = -0.33). Mealiness was averaged related to peeling ability (*r* = 0.48; Table 2.8) and to yellowness (*r* = -0.46; Table 2.8).

2.3.4.4 Sweetness

The sensory attribute sweetness showed significant year*region interactions and year*cultivar interactions (Table 2.5). In 2007, tubers from SG were with 17% significantly sweeter in taste than tubers from NG with 11 % (Table 2.6). In 2008, the opposite was found (NG: 12 %, SG: 9 %) and in 2009, there were no significant differences between sweetness notes in tubers harvested in Northern (8 %) and Southern Germany (9 %). In NG no significant differences in tuber sweetness were found in 2007 and 2008 (11 % and 12 %, respectively), while in 2009 the panel rated tubers with 8 % as the least sweet. In SG tubers from harvest years 2008 and 2009 showed no significant differences in tuber sweetness (both 9 %), while tubers harvested in 2007 were rated as the sweetest potatoes (17 %).

In 2007, the panel rated cvs Nicola (16 %) and Princess (15 %) as the significant sweetest potatoes compared to cv. Ditta (10 %). In 2008 and 2009, cv. Nicola showed the highest sweetness notes, too (14 % and 10 %, resp.), while the sweetness of cvs Princess and Ditta did not differ significantly. In all of the three years sweetness notes of Ditta were on a comparable level, while cv. Princess was rated by the panel as significant sweeter in 2007 compared to 2008 and 2009, in between no significant differences concerning tuber sweetness were observed (both 7 %). In cv. Nicola significantly highest sweetness notes were observed in 2007 (16 %) and 2008 (14 %) compared to 2009 (10 %, Table 2.6).

Sweetness correlated weak positively with the sum of temperatures (*r* = 0.27; Table 2.7). Starch concentration (*r* = 0.43), peeling ability (*r* = 0.31) and mealiness (*r* = 0.53) were positively related to sweetness (Table 2.8). Weak to averaged negative correlations were observed between nitrate concentration and sweetness (*r* = -0.26) as well as between yellowness and sweetness (*r* = -0.37; Table 2.8).

2.3.4.5 Bitterness

There were significant differences in the bitterness of potatoes according to cultivar and to the two-way interaction year*region (Table 2.5). The potatoes of the cultivar Princess had a significant higher bitter note (10 %) compared to cv. Ditta (5 %) and cv. Nicola (4 %), which were on a comparable level (Table 2.6).

The taste panellists scored tubers from NG from 2007 as the significant more bitter compared to the south region (9 % and 5 %, resp.), while in 2008 and 2009, no significant differences between both regions concerning bitter taste were found (Table 2.6). The panel scored tubers harvested in 2008 and 2009 in NG as least bitter (both 5 %) compared to tubers harvested in 2007, which were rated as the significant most bitter (9 %). In SG tubers from 2008 and 2009 had the strongest bitter notes (7 % and 6 %, respectively), and tubers from 2007 had the slightly bitter notes (5 %), whereby this effect was only significant between 2007 and 2008.

The taste panel scoring of bitterness was positively averaged related to nitrate concentrations (r = 0.46) and yellowness (r = 0.50) and negatively strong related to starch concentration (r = -0.64). Peeling ability (r = -0.41), mealiness (r = -0.50) and sweetness (r = -0.57) showed an average negative correlation to bitterness (Table 2.8).

Table 2.5: Test of fixed effects: ρ-values for year, region, cultivar and their interactions

Effect	Numerator *df*	Yield (dt ha^{-1})	Nitrate (mg kg^{-1} FW)	Starch (% in FW)	Peeling ability (%)	Yellowness (%)	Mealiness (%)	Sweetness (%)	Bitterness (%)
Year	2	**<.0001**	**0.0335**	**0.0302**	**0.0498**	**<.0001**	**<.0001**	**<.0001**	0.5000
Region	1	**0.0346**	0.0914	**0.0200**	0.5249	0.6738	0.1069	0.0544	0.3817
Cultivar	2	0.1141	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Year x region	2	**<.0001**	**0.0189**	**<.0001**	0.1389	**0.0031**	**<.0001**	**<.0001**	**0.0003**
Year x cultivar	4	0.4776	0.8581	0.0718	0.0688	**<.0001**	**0.0011**	**0.0109**	0.4795
Region x cultivar	2	0.7810	0.9514	0.1181	0.5046	0.2497	0.6066	0.1350	0.7104

ρ-values in bold represent significant effects

Table 2.6: Means and significant differences from ANOVAs of different parameters

		Yield (dt ha^{-1})	Nitrate (mg kg^{-1} FW)	Starch (% in FW)	Peeling ability (%)	Yellowness (%)	Mealiness (%)	Sweetness (%)	Bitterness (%)
Year									
2007		204.08 -	118.80 -	10.80 -	49.63 b	35.73 -	12.71 -	11.45 -	7.85 ns
2008		295.96 -	125.61 -	11.82 -	57.30 a	24.10 -	13.87 -	10.51 -	6.26 ns
2009		285.49 -	108.70 -	12.11 -	54.54 ab	26.62 -	8.51 -	8.26 -	5.82 ns
Region									
NG[a]		277.48 -	117.19 ns	11.30 -	51.88 ns	29.90 ns	10.99 ns	9.78 ns	7.11 ns
SG[b]		248.09 -	117.62 ns	12.06 -	56.82 ns	26.69 ns	12.40 ns	10.27 ns	5.88 ns
Cultivar									
Princess		251.73 ns	154.92 a	9.79 c	42.54 b	41.59 -	6.98 -	8.17 -	9.70 a
Ditta		264.29 ns	97.17 b	12.01 b	60.56 a	25.00 -	11.79 -	9.51 -	5.41 b
Nicola		282.80 ns	97.19 b	13.28 a	59.55 a	17.64 -	16.64 -	12.62 -	4.36 b
Year	Region								
2007	NG[a]	162.27 b B	120.70 a A	10.00 b B	48.54 ns	35.96 a A	8.50 b B	10.54 b A	8.79 a A
	SG[b]	291.01 a A	104.28 a B	12.89 a A	55.43 ns	29.45 b A	22.21 a A	16.61 a A	4.65 b B
2008	NG[a]	354.92 a A	108.50 b A	12.04 a A	58.24 ns	21.26 b B	16.33 a A	11.63 a A	5.34 a B
	SG[b]	229.00 b B	155.06 a A	11.72 a B	57.89 ns	26.83 a A	11.04 b B	9.13 b B	7.18 a A
2009	NG[a]	319.64 a A	99.03 a A	12.67 a A	55.73 ns	25.10 a B	9.80 a B	7.95 a B	5.49 a B
	SG[b]	240.81 b AB	113.11 a B	11.65 b B	52.97 ns	27.81 a A	6.87 a C	8.66 a B	6.23 a BA
Year	Cultivar								
2007	Princess	217.55 ns	155.43 ns	10.16 ns	47.08 ns	54.27 a A	11.17 b A	14.74 a A	10.68 ns
	Ditta	234.37 ns	85.75 ns	11.33 ns	53.87 ns	27.60 b A	10.40 b B	10.08 b A	5.78 ns
	Nicola	228.00 ns	96.30 ns	12.84 ns	55.00 ns	16.25 c A	24.50 a A	15.90 a A	3.70 ns
2008	Princess	261.68 ns	178.48 ns	9.79 ns	44.08 ns	33.17 a B	8.42 b AB	7.40 b B	8.67 ns
	Ditta	295.40 ns	109.56 ns	12.02 ns	67.19 ns	21.26 b B	15.02 a A	10.20 b A	5.65 ns
	Nicola	318.80 ns	107.30 ns	13.83 ns	62.91 ns	17.71 b A	17.63 a B	13.54 a A	4.46 ns
2009	Princess	275.95 ns	138.63 ns	10.52 ns	40.36 ns	36.63 a B	5.25 b B	6.69 b B	8.48 ns
	Ditta	263.10 ns	86.75 ns	12.73 ns	61.48 ns	24.34 b AB	9.16 ba B	8.31 ba A	4.55 ns
	Nicola	301.62 ns	92.82 ns	13.26 ns	61.22 ns	18.40 c A	10.59 a C	9.92 a B	4.54 ns

Means of yield, chemical compounds and sensory attributes denoted by different letters in the same column are significantly different at $\rho < 0.05$ by the Bonferroni test. Lower case letters indicate significant differences between regions or cultivars within a year. The capital letters indicate significant differences between respective region or cultivar over the years; ns = not significant.

[a] NG = Northern Germany

[b] SG = Southern Germany

Table 2.7: Correlation analysis between agronomic measurements and yield as well as chemical parameters of raw tubers and between the agronomic measurements and the sensory parameters of cooked tubers

Factor	Yield (dt ha^{-1})	Nitrate (mg kg^{-1} FW)	Starch (% in FW)	Peeling ability (%)	Yellowness (%)	Mealiness (%)	Sweetness (%)	Bitterness (%)
Soil texture	0.127	-0.171 *	-0.084	-0.082	-0.010	-0.098	-0.141	0.129
Soil quality Index	-0.207 **	0.116	0.086	-0.010	0.013	0.019	0.165 *	-0.172 *
pH (CaCl$_2$)	-0.153	0.173 *	0.124	0.104	-0.041	0.030	0.116	-0.160 *
P (CAL; mg kg^{-1}, 0-30 cm)	-0.118	0.050	-0.060	0.104	-0.017	0.054	0.078	0.065
K (CAL; mg kg^{-1}, 0-30 cm)	-0.058	0.157	-0.092	0.080	0.048	0.018	0.031	0.008
Seed stock	-0.136	-0.035	-0.121	-0.003	0.094	-0.057	-0.163	0.151
Seed treatment	-0.057	-0.013	-0.021	-0.019	0.001	0.022	0.103	0.021
Seed preparation	-0.155	0.107	-0.100	-0.094	-0.041	-0.038	-0.121	0.095
Preceding crop comb	0.066	0.056	-0.072	-0.060	0.079	-0.078	-0.094	0.135
Farm fertilizer	-0.091	0.015	-0.040	-0.044	0.059	0.003	-0.026	0.061
Organic Commercial fertilizer	0.131	-0.054	0.255 ***	0.104	-0.084	0.160 *	0.066	-0.178 *
Irrigation (mm)	0.379 ***	-0.100	-0.010	0.002	-0.049	-0.030	-0.021	-0.015
K-fertilizer (kg ha^{-1}) (sum of farm-produced and commercial fertilizer)	0.216 **	-0.039	-0.013	0.002	-0.085	-0.035	-0.050	-0.027
Days between planting and beginning of *P. infestans*	0.650 ***	-0.248 ***	0.296 ***	0.144	-0.184 *	0.239 **	-0.025	-0.241 **
Sum of temperature (01.06.-15.08.)	-0.120	0.028	0.068	0.099	-0.005	0.201 **	0.266 ***	-0.077
Sum of precipitation (01.06.-15.08.)	-0.348 ***	0.045	-0.088	-0.005	0.065	-0.062	0.027	0.032
Sum of global radiation (01.06.-15.08.)	0.319 ***	-0.152 *	0.198 **	0.158 *	-0.050	0.236 **	0.096	-0.208 **

Asterisks denote significant relationships between these two variables at $\rho<0.05$ (*);$\rho<0.01$ (**) and $\rho<0.001$ (***).

Table 2.8: Correlation analysis between chemical compounds in raw tubers and sensory parameters of cooked potatoes

Factor	Nitrate (mg kg^{-1} FW)	Starch (% in FW)	Peeling ability (%)	Yellowness (%)	Mealiness (%)	Sweetness (%)	Bitterness (%)
Nitrate (ppm in FW)		-0.512 ***	-0.343 ***	0.278 ***	-0.330 ***	-0.258 ***	0.463 ***
Starch (% in FW)			0.602 ***	-0.596 ***	0.610 ***	0.432 ***	-0.637 ***
Peeling ability				-0.430 ***	0.477 ***	0.309 ***	-0.408 ***
Yellowness					-0.455 ***	-0.368 ***	0.504 ***
Mealiness						0.532 ***	-0.499 ***
Sweetness							-0.572 ***

Asterisks denote significant relationships between these two variables at $\rho<0.05$ (*);$\rho<0.01$ (**) and $\rho<0.001$ (***).

2.4 Discussion

2.4.1 Tuber Yield

In 2008 and 2009, total tuber yields were significantly higher in Northern Germany than in the Southern growing area (Table 2.6). The significantly lower yields in Northern Germany in 2007 could be explained by the prevailing weather conditions. Due to the annual above-average precipitation amount of 1000 mm in Northern Germany with high amounts in May and June combined with high temperatures, potato plants were infested with *P. infestans* very early, interrupting the growth period that year. This is consistent with the observed inverse weak correlation between precipitation amount and total tuber yield (r = -0.35; Table 2.7). This finding is in agreement with Hospers-Brands et al. (2008), who reported that the length of growth period is a determining factor for yield formation. Yield formation was strongly related to the time interval between planting and the beginning of infestation with *P. infestans* (r = 0.65) and weakly correlated with the sum of global radiation (r = 0.32) (Table 2.7). Light absorption is required for photosynthesis and carbohydrate production. Therefore, an early growth and crop cover, as well as a healthy leaf population at the time of maximum day length in June and July, are essential for yield formation (Kolbe 1994). This is also demonstrated in our study. The significantly higher yields in Southern Germany in 2007 and in Northern Germany in 2008 can be explained by the high global radiation between April and July in these regions (s. Table 2.2). Already Klapp (1967) and Kolbe (1994) described a decrease of tuber yields due to a reduction of radiation intensities. Early infestation of the crops with *P. infestans* - as we witnessed in Northern Germany in 2007 - may superimpose the effect of global radiation. In addition, adequate water supply is essential for yield formation (Miller and Martin 1983). Potatoes are more sensitive to water stress than many other crops, due to their sparse root system that is concentrated in the upper 30-cm soil layer (Opena and Porter 1999). Especially sandy soils, which in the present study dominate in the Northern Germany region, suffer from a water deficit, which normally causes lower yields. However, the majority of farms participating in this study irrigated their sandy soils, which on average led to an additional yield of more than 20 %. Indeed, we found a positive weak relationship between yield and irrigation (r = 0.38; Table 2.7). This is in good agreement with the studies of Roth et al. (1987), who found an increase of potato yields in response to irrigation in field experiments.

2.4.2 Nitrate Concentrations

The nitrate concentrations of individual species vary considerably within each maturity group (Kolbe 1990). On average, early cultivars show higher concentrations (190-345 NO_3 mg kg^{-1} FW) compared to late cultivars (140-220 NO_3 mg kg^{-1} FW) (Grassert and Bartel 1987; Hippe 1996; Reents and Tucher 1997). In 2004, the European Union introduced maximum nitrate levels of 250 mg kg^{-1} for baby food as well as processed cereal-based foods for infants and young children (Anonymous 2004). The significant cultivar effect also reflected these results (Table 2.5). With 155 mg (NO_3 kg^{-1} FW) for cv. Princess and 97 mg (NO_3 kg^{-1} FW) for cv. Ditta and cv. Nicola (Table 5), nitrate concentrations were significantly beneath the maximum nitrate limits set by the EU. Nitrate concentration can be also influenced by climatic conditions, such as global radiation, water supply and temperature variation (Marschner 1984), as well as by amount, kind and timing of N supply by organic fertilizer, stage of maturity and harvest timing (Kolbe 1990; Reents and Tucher 1997). In the present study, we found a weak negative relationship from the time interval between planting to the beginning of *P. infestans* on nitrate formation (r = -0.25; Table 2.7). Especially in tubers from Southern Germany harvested in 2008, significantly higher nitrate concentrations were measured (Table 2.6). Some regions in Southern Germany suffered under an infestation with *P. infestans* leading to a shortened growth period with high tuber nitrate concentrations in certain batches. This is in good agreement with Kolbe (1990), who found that the length of life and quality of the canopy has an effect on the nitrate concentration of tubers. According to Nitsch (2003) an increase of late blight-susceptibility from Grade 3 to Grade 6 led to an approximate doubling of nitrate levels in the harvested tubers. The damage of the canopy leads to a reduction in photosynthesis and of the formation of carbohydrates (starch) in the tubers and so to an increase in nitrate.

2.4.3 Starch Concentrations

Starch concentration is one of the main characteristics for the cooking type and a good measure for the prediction of cooking quality (Stark and Love 2003). Waxy cultivars have starch concentrations between 9 and 12 % of the fresh weight, predominantly waxy cultivars between 12 and 15 % and mealy ones between 15 to 18 % (Wölfel 2002). Starch contents and compositions are mainly genetically determined and vary significantly dependent on cultivar (Cottrell et al. 1995; Haase and Plate 1996; Jansen et al. 2001). According to the description list of cultivars of the *Federal Office of Plant Varieties* (Bundessortenamt 2011), all three cultivars selected in the present study are listed as waxy cultivars. With 12.0 % for cv. Ditta as well as 9.8 % for cv. Princess, starch concentrations in both cultivars were in the classified range for waxy cultivars. With 13.3 % for cv. Nicola, tuber starch concentration was above the values for waxy cultivars. Starch concentration can be also influenced by environmental conditions in the vegetation period (Kolbe 1990; Liu et al. 2003). With the exception of 2007, higher starch concentrations were always measured in tubers from Northern Germany as compared to tubers from Southern Germany. In 2007 in Northern Germany, the environmental conditions during the growing season influenced starch formation and led to the significant lowest concentrations. High precipitation favoured the spread of *P. infestans*, which interrupted the ripening of the tubers and the continued starch formation. The correlation analysis showed a weak but significant relationship between time interval between planting and the beginning of *P. infestans* and starch accumulation (r = 0.30; Table 6). The results are in good agreement with Gilmore (1905) and Thygesen et al. (2001), who found that starch concentration is higher in mature tubers and lower in immature potatoes. According the correlation analysis, the application of organic commercial fertilizer had a positive weak influence on starch formation (r = 0.26; Table 2.7). Highest starch concentrations were measured in tubers from the variant without N-application. In contrast, tubers from plants receiving organic commercial fertilizer containing high N-contents had lower starch concentrations. This is also described by Neuhoff et al. (1997), Schulz et al. (1997) and Möller and Kolbe (2003), who observed a decrease of starch concentrations after applying organic fertilizer.

Furthermore, correlation analysis showed a negative correlation between nitrate concentration and starch concentration (r = -0.51; Table 2.8). A reduced photosynthetic capacity leads to a reduction of carbohydrates (starch) accumulation in the tubers so that there is a percentage increase of nitrate (concentration effect) (Marschner 1984).

2.4.4 Sensory attributes

2.4.4.1 Peeling ability

The panel detected a significant cultivar effect on peeling ability. Cultivars with the highest starch concentrations, cvs Ditta and Nicola, showed with 60.6 % and 59.6 %, the best peeling ability. The correlation analysis also calculated a strong positive relationship between peeling ability and starch concentration (r = 0.60; Table 2.8). Furthermore, the taste panel was able to detect differences in the peeling ability of the tubers grown in different years. Potatoes from the harvest in 2008 and 2009 showed a better peeling ability than those from 2007, especially tubers from Northern Germany (Table 2.6). It can be assumed that the peeling ability is connected with the weather conditions in 2007, resulting in lower tuber starch concentrations in that year. Nitrate concentration correlated weak negatively with peeling ability (*r* = -0.34; Table 2.8). This is in good agreement with our result that nitrate concentration is negatively correlated with starch concentration (*r* = -0.51; Table 2.8). It can be assumed that immature tubers, in which higher levels of nitrate concentrations were measured, had a poorer peeling ability.

2.4.4.2 Flesh colour

The flesh colour of cooked potatoes depends on the flesh colour of raw tubers (Burton 1989). The flesh is tinged with yellow to a greater or lesser extent due to the presence of carotenoids (Burton 1989). The concentration of carotenoids is a heritable characteristic. Also the panel rated cv. Princess in all years as the most yellowness potato, followed by cvs Ditta and Nicola (Table 2.6). This is in good agreement with the cultivar characteristics according of *Federal Office of Plant Varieties* (Bundessortenamt 2011), whereby cv. Nicola is classified as a light yellow and cv. Ditta as a yellow potato. Cv. Princess is characterized as a tuber with deep yellow flesh (The European Cultivated Potato Database 2012). But taste panellists detected differences in flesh colour from different years*regions as well as years*cultivars. Samples from Northern Germany in 2007 had significant higher yellow intensity compared to Southern Germany, while in 2008 tubers from Southern Germany showed the highest yellow intensities (Table 2.6). Carotenoids belong to a larger class of compounds called terpenes. Desjardins et al. (1995) found higher levels of sesquiterpenes, a subform of terpenes, in raw potatoes after tuber damage or microbial attack. Zacharius and Kalan (1984) demonstrated that fungal and bacterial infections (*Erwinia carotovora* ssp. *atroseptica*, *Phytophthora infestans*) lead to an increase of the potato stress metabolite solavetivone, a sesquiterpene. In our study perhaps, the fungal infection of the potatoes with *P. infestans* in 2007 in Northern Germany and in 2008 in Southern Germany resulted in an increase of carotenoids and so in yellowness. Differences concerning cultivars and yellowness were also detected. Because infestation in 2007 in Northern and 2008 in Southern Germany led to lower tuber starch and higher tuber nitrate concentrations, the correlation analysis ascertained a high negative relationship between starch and yellowness (*r* = -0.60; Table 2.8) and a positive weak relationship between nitrate concentration and yellowness (*r* = 0.28; Table 2.8). Furthermore, a negative relationship between peeling ability and yellowness was found (*r* = -0.43; Table 2.8), again as a result of the high starch concentrations of mature tubers.

2.4.4.3 Mealiness

Texture, like flavour, is a complex and important determinant of consumer preference (Baier 1986; Van Marle et al. 1997; Thygesen et al. 2001; Van Dijk et al. 2002; Taylor et al. 2007). Many chemical components are involved in texture formation (Thygesen et al. 2001; Dresow et al. 2009). Texture is influenced by starch grains in the cell and the cell wall components (McComber et al. 1994; Martens and Thybo 2000). The dry matter content consists of 60-80 % starch, and is highly associated with the texture of cooked potatoes (Burton 1989; McComber et al. 1994). In the present investigation, a good positive correlation between starch concentration and the sensory attribute mealiness was ascertained (r = 0.61; Table 2.8). This is in good agreement with the result of Van Dijk (2002), who found a correlation between mealiness and high dry matter content, too. Van Merle et al. (1997) also stated that potato texture can be determined by the degree of tuber´s mealiness. However, in the sensory study of True and Work (1981) no correlation was observed. According Thygesen et al. (2001), a simple measurement of the dry matter content of raw potatoes gives significant information on the sensory texture of the potatoes after boiling. Mealiness refers to the feel of the potato in the mouth (Warren and Woodman 1974) and is regarded as being one of the most important cooking quality properties of table potatoes (Varis 1970). According to Heinze et al. (1955), mealiness cannot be used as the sole criterion for cooking quality because some of the mealiest potatoes peel badly and do not hold their shape well enough to make an attractive boiled potato. The consumer´s preferences for either mealy and dry potatoes or firm potatoes are very different depending on country, age and usage (Thybo and Martens 1999). Substantial differences in mealiness have been found to be a genetic characteristic (Unrau and Nylund 1957; Varis 1970; Van Marle et al. 1997; Jansky 2008). In the present study, the panel members also detected textural differences due to cultivar. Samples from the cv. Nicola were assessed as the mealiest potato, followed by cv. Ditta and cv. Princess (Table 2.6). According to the *Federal Office of Plant Varities*, cvs Nicola and Ditta are classified as low mealy tubers (Bundessortenamt 2011), while cv. Princess is described as a firm potato (Anonymus 2012). Van Marle et al. (1997) found a pronounced cultivar effect, too. In addition to the genetically determined characteristics of the fresh product, agronomic as well as processing conditions have an impact on the sensory-perceived texture of the cooked potato (Faulks and Griffiths 1983; Ridley and Lindsay 1984; Van Dijk et al. 2002). In the study of Faulks and Griffiths (1983) taste panellists scored textural differences in mashed potatoes from different sites. A regional effect was also demonstrated in our study. With the exception of 2007, samples from Northern Germany were the mealiest compared to those from Southern Germany (Table 2.6). This lower mealiness in Northern Germany in 2007 could be explained by the infestation with *P. infestans* in this year, preventing ripening and further starch formation. That a shortened growing season leads to a lower mealiness is also confirmed by the correlation analysis (Table 2.7). A weak positive relationship was found between the time interval between planting and beginning of *P. infestans* and mealiness (r = 0.24; Table 2.7). Consequently, the correlation analysis shows a good correlation between nitrate concentration and tuber yellowness (Table 2.8). Furthermore, the correlation analysis ascertained weak positive effects of sum of temperature and sum of global radiation on mealiness (r = 0.20 and 0.24; Table 2.7). The higher average temperatures and global radiation in 2008 and 2009 in Northern Germany may have increased the intensity of mealiness (Table 2.2). Varis (1970) detected an effect of increased temperature sum and mealiness, too. A high solar radiation leads to an increased photosynthetic capacity and thus to higher levels of starch formation in the cells (Kolbe 1994). In the present study, starch concentration correlates very closely with mealiness, whereby consequently the global radiation affects tuber mealiness, too. Furthermore, mealiness correlated positively with peeling ability (r = 0.48; Table 2.8). Because peeling ability correlated positively with starch concentrations and starch concentrations correlated positively with mealiness, we also found a positive relationship between peeling ability and mealiness.

2.4.4.4 Sweetness

Sweetness in tubers is mostly associated with mono- or disaccharides released by starch hydrolysis during the heating process (Dinehart et al. 2006; Jansky 2008). The correlation analysis ascertained a positive correlation between starch concentration and sweetness (r = 0.43; Table 2.8). This is in contrast to Jitsuyama et al. (2009), who found a negative relationship between starch concentration and sweetness. In the present study, the panel were able to detect variation in sweetness in tubers of different years, regions and cultivars (Table 2.5). The interaction year*region showed in 2007 significant higher sweetness notes in tubers from Southern Germany, while in Northern Germany in this year the lowest sweetness intensity was measured (Table 2.6). The infestation with *P. infestans* in 2007 in Northern Germany led to an interruption of starch synthesis, which consequently resulted in less sweetness. According the taste panel, cv. Nicola, the cultivar with the highest starch concentrations, had in every year the highest sweetness note. According the correlation analysis, a positive weak relationship between sum of temperature and sweetness was found (r = 0.26; Table 2.7). It can be assumed that higher temperatures in the vegetation period led to a starch hydrolysis resulting in mono- or disaccharides, which gave the tubers the sweetness note.

2.4.4.5 Bitterness

Bitterness has been reported as a sensory deterrent for vegetable preferences and consumption (Drewnowski and Gomez-Carneros 2000). A bitter taste is usually associated with increased toxic glycoalkaloid concentration in the tubers (Sinden et al. 1976; Ahmed and Müller 1979; Johns and Keen 1986; Maga 1994; Zarzecka and Gugala 2007), which was not subject of the present investigation. We found a positive relationship between bitterness and nitrate concentration (r = 0.46; Table 2.8). This result is in good agreement with Cieslik (1997). She found that nitrates and nitrites have a direct effect on sensory quality due to formation of amides and amines, which are responsible for bitter taste. For all years, the taste panel classified cv. Princess, the cultivar with the highest nitrate concentration, as the cultivar having the strongest bitter note (Table 2.6). In 2007, potatoes grown at northern sites had more intense bitter notes than those from southern production locations. This phenomenon could be explained with the infestation with *P. infestans* and the formation of the stress compound terpene. Terpenes are responsible for vegetable bitterness up to pungency (Drewnowski and Gomez-Carneros 2000). Furthermore, the terpene family includes the carotenoids, which are responsible for the yellowness of the flesh. Due to this, bitterness correlated positively with yellowness (r = 0.50; Table 2.8). About all three years, a significant correlation between an increase of bitter intensity and a decrease of sweet intensity was observed. Sweetness and bitterness are negatively correlated with each other (r = -0.57; Table 2.8). Schonhof et al. (2004) found in cruciferous vegetables that sweetness declines in proportion to an increase in bitterness. The negative correlation between nitrate concentrations and starch concentration, tuber mealiness and peeling ability, respectively, was described above. The correlation analysis confirms these findings and calculated negative relationships between starch concentrations and bitterness (r = -0.64), mealiness and bitterness (r = -0.50) and peeling ability and bitterness (r = -0.41) (Table 2.8).

2.5 Conclusions

While there are a lot of studies about chemical components influencing the flavour of cooked potatoes, information about the effect of cultivar types, agronomic measures and different weather conditions on sensory quality is lacking. This knowledge could help develop new approaches to improve the quality of organic potatoes and increase the purchase of raw organic potatoes.

We investigated in three subsequent years (2007-2009) and two different regions in Germany, the effect of three chosen cultivars (cvs Princess, Nicola and Ditta) and selected agronomic measures on yield, starch and nitrate concentrations and cooking quality of organic potatoes in the skin. The results of this study show that the length of growth period had a main influence on yield and quality formation of tubers. An early interrupted growth period due to the infestation with *P. infestans* or low temperatures and low global radiation led to lowest tuber yields, high nitrate and low starch tuber concentrations. A strong correlation between starch concentration and sweetness or mealiness as well as between nitrate concentration and high bitter notes was detected in this study. An interrupted growth phase leads to stress symptoms in the plant and enhances the formation of undesirable qualities. Stress resulting from weather and climate is not under the control of the potato grower. However, through proper management, the damage to yield and tuber quality caused by environmental factors can be minimized. An adequate nutrient supply, especially with N, and an additional irrigation on sandy soils may contribute to safeguarding the yield and quality attributes. The choice of cultivar is an important measure, too. The knowledge about specific morphological features of different potato cultivars is helpful in the choice of cultivar adapted to the specific site conditions.

Due to the occurrence of *Phytophthora infestans*, which possibly compensated the influence of agronomic measures on the sensory quality of organic potatoes in the skin, follow-up investigations on these measures should be conducted, to further improve the quality of organic potatoes and thus meet the consumers’ market demands.

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3 Effect of different defoliation systems of ryegrass-clover on yield and selected quality parameters of organic potatoes (*Solanum tuberosum* L.) for industrial processing at harvest and after storage

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Abstract

The nitrogen supply plays an important role in achieving quality characteristics in organic potato farming. Different defoliation systems of ryegrass-clover may influence the amount of fixed nitrogen available to the tubers. In a field experiment the effect of different defoliation systems (cutting, mulching and a combination of them) of the pre-crop ryegrass-clover on selected quality attributes of organically grown potatoes, destined for processing into French fries (cv. Agria) or crisps (cv. Marlen), were conducted in two consecutive years (2003 and 2004). Parameters studied included compounds related to the sensory properties of potato food (tuber dry matter, starch, reducing sugars) as well as nutritional quality (nitrogen, minerals). Selected agronomic parameters such as total tuber yields and tuber size distribution were also compared. Furthermore, the influence of additional slurry fertilization and 4-months of storage on these parameters were investigated.

Total yields and portion of tuber yield 50-60 mm were significantly affected by the pure mulching variant in 2003. In 2003, the starch concentration at harvest, as well as after storage, was above the required minimum of 22 % (cv. Marlen) and 19 % (cv. Agria), while in 2004 this was slightly beneath these values. In 2004, a significant increase of starch concentration by the pure cutting variant was observed. In both years, mulched ryegrass-clover caused a decrease in tuber DM contents of 2.10 % and 3.54 %, respectively, compared to the cutting-systems. Fertilization significantly decreased DM and starch concentration. In 2004, tubers from the cut-used cv. Marlen had with 2.1 g kg^{-1} FM reducing sugar concentration above the required maximum of 1.5 g kg^{-1} for crisps. In addition, storage led to a 3-5-fold increase of reducing sugars concentrations in the tubers in this year. After slurry fertilization 8.8 % higher N contents and up to 36 % higher K concentrations were measured. Mulching of the pre-crop combined with slurry application led to an up to 61 % higher tuber K concentration compared to the cutting-system.

The results indicate that different defoliation systems of the pre-crop ryegrass clover and slurry fertilization had only minor effects on internal tuber quality attributes. Quality parameters were more affected by the prevailing weather conditions in combination with the genotype of different potato cultivars.

Keywords: Potato crisps; Cultivar; Dry matter concentration; Fertilization; French fries; Ryegrass-clover; Mineral elements; Reducing sugars; Starch; Nitrogen

Abbreviations

C	cutting
CV	cultivar
DM	dry matter concentration
DS	defoliation system
FW	fresh weight
K	potassium
LSD	least significant differences
Mg	magnesium
MU	mulching
N	nitrogen
P	phosphorous
REP	replication (block)
SF	slurry fertilization
STOR	time of assessment

3.1 Introduction

Due to health and safety concerns, the demand for organically grown potatoes has gradually increased worldwide. In 2009, 7.3 % of the German table potato cultivation area was used for organic potatoes, whereas for processing potatoes this was only 1.1 % of the absolute cultivation area (AMI 2010). As the demand for convenience-products is rising, organic potato cultivation for industrial processing into French fries or potato crisps may be a new source of income for growers (Kuhnert et al. 2004). The requirements on raw material quality for processing potatoes are high, however, and differ from those for table potatoes. In addition to high external and internal quality standards, the potatoes need to have good storage stability, low damage sensitivity, as well as a certain grading size. Potatoes used for French fries and crisp processing are mostly produced in controlled contract farming. Therefore, slightly different requirements exist for tuber qualities, depending on processors used. The *conventional* French fries industry requires a tuber size of 55 mm, whereas the *organic* French fries industry currently demands raw material >35 mm and a proportion of at least 60 % of tubers >50 mm (Haase et al. 2007c). The crisp industry does not differentiate between conventionally and organically cultivated potatoes and tuber sizes between 40 and 65 mm are required (Böhm 2003). In addition, high levels are set for the internal quality characteristics with no differentiation between organically and conventionally grown potatoes. Sufficient starch contents with concurrently low contents of reducing sugars are of particular importance for processing potatoes. The starch content in processing potatoes should be between 14 and 18 % of fresh weight (FW) for French fries and between 16 and 20 % of FW for crisps to ensure crispness, good texture and taste of the final product. Furthermore, concentrations of reducing sugars should not exceed 2.5 g kg^{-1} FW for French fries and 1.5 g kg^{-1} FW for crisps (Schuhmann 1999). High concentrations of reducing sugars result in dark brown colouring (Mazza et al. 1983) with a bitter taste (Roe and Faulks 1991) and may influence the formation of the potential cancer-causing acrylamide (Mottram et al. 2002; Haase et al. 2003; Granda et al. 2005; Ohara-Takada et al. 2005). Potato tubers for processing are generally stored at temperatures of about 8 to 12°C (Matsuura-Endo et al. 2006) because low-temperature (2-4°C) storage of potato tubers causes an increase in reducing sugars, as well as changes in dry matter (DM) and starch concentrations (Misra and Kulsherstha 2003).

Sensory quality characteristics of the processed products like colour, smell and taste are not only influenced by reducing sugars, DM and starch, but also by nitrogen and mineral substances, potassium (K), magnesium (Mg) and phosphorous (P) (Pawelzik 2000).

Tuber nitrogen concentration depends on the level and course of nitrogen supply by nitrogen rich crop residues or organic fertilizers, cultivar and the degree of maturity (Haase et al. 2007c). High nitrogen can reduce starch (Hunnius 1972) and reducing sugar concentrations (Kolbe 1990) and result in a bitter taste (Kolbe 1990).

Therefore a balanced nitrogen supply is indispensable to yield and quality formation (De Wilde et al. 2006, Haase et al. 2008). In organic farming systems, N-input in the crop rotation occurs mainly by legumes. In the North-German climate, red clover (*Trifolium pratense* L.), which has a high N_2-fixation potential, is cultivated in mixtures with ryegrass (*Lolium perenne* L.). Ryegrass-clover mixtures are used as fodder for ruminants. They produce manure or liquid manure, which can be used variably in the crop rotation to further improve the nitrogen supply. Farms without animal husbandry integrate ryegrass-clover mixtures in their crop rotation. Growth is mulched repeatedly and remains on the fields (Stopes et al. 1996). The grass-clover mixture improves soil fertility by adding organic matter (Asmus 1991), thereby increasing N availability for succeeding crops (Stute and Posner 1995). Sward cultivation duration, the seed-mixture and the defoliation system of the preceding crops are of vital importance for the amount of nitrogen fixed by succeeding crops (Loges et al. 1998).

Loges et al. (1998) and Dreymann (2005) found that different grass-clover defoliation systems, which differ in C:N-ratios result in different degrees of N_2-fixation. Dreymann (2005) investigated the impact of three defoliation systems (3-cuts + 1x mulched; 2-cuts + 2x mulched; 4x mulched) of red clover and grass, discrete or in mixtures, on: dry matter productivity, N-accumulation, and yield performance of subsequent winter wheat. They found that the N_2-fixation potentials of the mulched only swards were significantly reduced. Furthermore, a significant interaction between seed mixtures and defoliation systems on grain-DM-yield were demonstrated. The defoliation systems as main factor had no effects on grain-DM-yield and grain N-uptake, but the grain-protein content was significantly increased by the mulching treatment.

The aim of the current study was to examine the effect of different defoliation systems of rye-grass clover and fertilization on total yield as well as on selected external and internal quality attributes of subsequent organically grown potatoes for processing in two consecutive seasons (2003 and 2004). The second aim of this study was to investigate the influence of a 4-months storage period at 8°C on selected internal quality parameters.

3.2 Methods

3.2.1 Site Description and Measurements

The study was conducted at the Lindhof Research Farm at the University of Kiel, Germany (53°40´N; 10°35´E), certified organic since 1997. The farm is located 29 m above sea level in a young moraine area with a total annual rainfall amount of 785 mm and a mean annual air temperature of 8.7°C (DWD). The soil textures of the experimental site were sandy loam in 2002/2003 and loamy sand in 2003/2004. The soil type was a brown soil, luvisol, pseudogley-leached brown soil, kolluvisol.

Daily weather data for the growing season of ryegrass-clover mixtures (2002 and 2003) and the subsequent potatoes (2003 and 2004) were obtained from an official weather station (Kiel-Holtenau), which is approximately 20 km from the experimental fields. The three years were characterized by different weather conditions (Table 3.1). 2002 was characterized by high summer- and total annual precipitations. Especially, in July and October abnormal high amounts of precipitation were measured. In 2003, all three-summer months were remarkably warmer than the average (Table 3.1). The prolonged high-pressure weather conditions resulted in higher-than-average sunshine duration and led to an extensive rainfall deficiency. After a below-average amount of precipitation in April and May in the year 2004, the months June and July showed higher amounts of precipitation with a lower sunshine duration in the summer months (Table 3.1).

Table 3.1: Monthly mean air temperature (°C), sum of precipitation (mm) and mean hours of sunshine (h) at the German weather station in Kiel-Holtenau, 20 km from the experimental sites (2002- 2004)

Year	2002			2003			2004		
	°C	mm	h	°C	mm	h	°C	mm	h
Jan	3.3	79	29	1.1	53	17	0.7	84	14
Feb	5.1	116	87	-0.8	8	90	3.1	75	89
Mar	5.1	44	121	4.7	20	161	4.7	40	125
Apr	7.5	45	157	8.0	51	228	8.7	40	202
May	13.1	40	200	13.0	80	236	11.6	28	209
Jun	16.4	80	236	17.1	42	249	14.3	84	192
Jul	17.6	227	187	19.5	28	249	15.8	87	190
Aug	19.9	82	224	19.1	22	251	18.3	99	235
Sep	15.1	17	196	14.7	38	207	14.3	81	178
Oct	8.0	119	88	6.7	71	156	10.5	41	109
Nov	4.8	86	36	7.1	62	54	5.8	44	66
Dec	0.1	27	47	3.9	48	56	3.4	70	34
Mean/sum	9.7	962	134	9.5	523	162	9.3	773	137

The different weather conditions also influenced the epidemic spread and the intensity of infestation with *Phytophthora infestans* in the experimental years. Due to below-average precipitation and high radiation in 2003, there was an infestation with *P. infestans* at the beginning of July. However, the fungus did not continue to proliferate, so that the intensity of infestation did not exceed 20 %. In 2004, a *P. infestans* epidemic also started around mid-July and progressed steadily; by early August 95 % of the canopy was infected.

3.2.2 Design and Crop Management

Experiments were conducted in two consecutive seasons (2003 and 2004) on different fields. In 2003, the experiment was carried out as a two sub-plot factor combination and in 2004 as a three sub-plot factor combination. Cultivars used were Agria and Marlen, mid-early types typically grown for processing of French fries (cv. Agria) and potato crisps (cvs Agria and Marlen) (Haase et al. 2005, Krause et al. 2005). In 2003, three defoliation systems of clover grass were prepared: 3-cutting (3C), 2-cutting + 1x mulching (2C+1MU) and 3x mulching (3MU). In 2004, a 1x mulching treatment (1MU) and additional slurry fertilization were added (Table 3.2). These different defoliation systems (DS) were the main-plots, the cultivars (CV) the sub-plots and in 2004 a slurry fertilization (SF) as sub-sub-plots. All factors with their factor levels are listed in Table 3.2.

Table 3.2: Factors and factor levels of the experiment

Factor	Factor levels
1. Defoliation systems of ryegrass-clover	1.1 3-cutting (3C)
	1.2 2-cutting + 1x mulching (2C + 1MU)
	1.3 3x mulching (3MU)
	1.4 1x mulching[*1] (1MU)
2. Potato cultivar	2.1. Agria (French fries)
	2.2. Marlen (Crisps)
3. Year	3.1. 2003 (crop year potato)
	3.2. 2004 (crop year potato)
4. Slurry fertilization	4.1. without slurry
	4.2. with slurry (75 kg N_t ha^{-1})[*1]

[*1] only 2004

For the establishment of the ryegrass-clover mixture, red clover (*Trifolium pratense* L. cv. Pirat) and ryegrass (*Lolium perenne* L. cv. Fennema) were used in a seed rate of 8 and 15 kg ha^{-1}, respectively. The potato pre-crop was undersown in barley grown for whole-crop silage. In the subsequent year, the different ryegrass-clover defoliation systems were applied to randomized plots in four replicates (REP). After cultivation in the subsequent spring, the main plots were split and used to cultivate the potatoes.

In case of harvest, ryegrass-clover was cut by a rotary mower and removed from the field. Mulching was carried out with a flail-mower, whereas the mulched material remained on the field. Stubble height of both systems was 5 cm. Harvest was carried out in both years by the same time at three dates: The first defoliation was carried out at the end of May. At 6-week intervals, the second (early July) and the third defoliation (end of August) were carried out. One exception demonstrated the 1MU variant in 2004, which was only mulched at the end of August. Before planting the potatoes in spring, the different ryegrass-clover plots were first cultivated by a rotovator and a plough, followed by the soil separation technique (track width 1.65 m, Grimme BF 200 / CS 1500, Damme, Germany). In 2004, slurry fertilizer (75 kg N_t ha^{-1}) was applied using a trailing hose. All seed tubers were pre-sprouted, kept in chitting boxes (600x400x160 mm; Ringoplast, Ringe, Germany), warmed to 18-20 °C for 2-3 days and to 10-12 °C for the subsequent 5-6 weeks and illuminated with neon lamps (light colour 930, 100 W t^{-1}). Seed tubers were planted in rows 0.75 m apart, at a depth of 8-10 cm. Further cultivation of the experimental fields (weed control, plant protection measures) occurred under customary circumstances (Table 3.3). *P. infestans* was assessed weekly with haulms dying as a percent of diseased leaf area following the scheme given by James (1971). Aboveground crop development was recorded according to the BBCH growth stages for potatoes given by Hack et al. (1993). All important site factors as well as cultivation data are summarized in Table 3.3.

Table 3.3: Soil, site- and experimental details

	2003	2004
Soil characteristics before planting		
pH ($CaCl_2$)	5.5	6.0
K (CAL) (mg kg^{-1}; 0-30 cm)	56 (at planting)	73 (at planting)
NO_3-N (kg ha^{-1}; 0-30 cm)	14.6	16.0
N_t (% DM; 0-30 cm)	0.13	0.13
Site- and experimental details		
Type of soil	sL	lS
Soil points	40-45	40-45
Preceding crop	ryegrass-clover (Table 3.2)	ryegrass-clover (Table 3.2)
Cultivation	plough, break in spring, soil separation technique	plough, break in spring, soil separation technique
Fertilization	120 kg ha^{-1} K_2O (May 9th)	120 kg ha^{-1} K_2O (March 4th)
Plant protection	2x copper ($\sum$ 1.2 kg ha^{-1})	1x copper (0.6 kg ha^{-1})
Chitting	yes	yes
Dressing	no	no
Date of planting	22. April	28. April
Main plot size (m x m)	14 x 13.2	15 x 13.2
Subplot size (m x m)	14 x 6.6	15 x 6.6
Tending strategies	3x roller-type roll hoe, 1x hilling	2x roller-type roll hoe, 1x hilling
Beginning of *P. infestans*-infection	09. July	10. July
Sprinkler irrigation	no	no
Date of harvest	17. September	15. September

3.2.3 Sampling and Analysis

Total yield of ryegrass-clover mixtures and the potential harvestable shoot matter of the mulching crops were determined on an area of 0.25 m^2 in four-point replications per term of defoliation system. The plant material was separated into clover and grass. In addition the remaining above-ground biomass of the ryegrass-clover residues was measured in autumn (18/10/2002, 20/10/2003) on a sampling area of 0.25 m^2. The clover-grass-residues were composed of sprout material of the last growth, stubble and in the case of mulching swards of old mulch. From the cleared areas, root samples were taken using a root auger (diameter 8 cm, Eijkelkamp) at a depth of 0-30 cm. The roots were rinsed out in a hydropneumatic root-washer and collected in a 1 mm-filter. All plant samples were dried at 65 °C for 20 h and grounded (1 mm sieve) with a laboratory cutting mill (Cyclotec 1093, Foss, Rellingen, Germany). Nitrogen-content and C:N-ratio were determined with the Near-Infrared-Reflection-Spectroscopy-method (NIRS 5000, Foss, Rellingen, Germany). The calculation was done with WinISI calibration software

(Infrasoft International, Pennsylvania, USA). Calibration was carried out using values of the C/N-analyzer Vario Max C/N (Elementar Analysesysteme, Hanau, Germany) according to the DUMAS-method.

At harvest, the potato crop was lifted with a two-row rake swather (RL-1500, Grimme, Damme, Germany). All potatoes from two inner harvest rows of the plots were collected and packed in air-permeable bags. After 2-3 weeks of dark storage with a fresh-air supply at 15 °C for wound healing, the total weight of the potatoes per plot was determined. A sample of 25 tubers was taken for future scoring. The remaining potatoes were graded with the sorting-machine (SET 604 CK, Skals, Denmark) into four fractions <40, 40-50, 50-60 and >60 mm. Each fraction, as well as wasted potatoes, was weighed. Then, all tubers >40 mm were mixed and 8 kg were packaged and transported for further processing. The remaining tubers were stored in boxes for four months at 8 °C in a potato-storage facility (Gaugele, Iffeldorf, Germany).

Tuber N-content was measured after freeze-drying and grinding (1 mm sieve, Cyclotec 1093) tuber samples using the NIRS-procedure (NIRLab N-200, Büchi, Flawil, Switzerland). The examination of the reflection data was done with the program NIRCAL 4.21 (Büchi, Flawil, Switzerland). A quantitative laboratory analysis was carried out with the CNS-elemental analyzer for calibration (HEKATECH, Wegberg, Germany).

Determination of DM and starch concentration and reducing sugars were conducted at harvest and after a 4-months storage period at 8 °C under controlled conditions. For the assessment of tuber DM and starch concentrations, as well as sugar concentrations, sub-samples of 5 kg per plot (graded >40 mm) were washed with tap water, and weighted in water with a KUV 2000-balance (Fischer KG, Bielefeld, Germany). Specific gravity was determined and used for calculating DM and starch concentrations according to Haase (2003).

DM concentration of the mashed samples was calculated after measuring the weight loss by heating at 105 °C in an oven dryer (AACC 1993a). The remaining moisture concentration of the lypophilised and ground samples was also measured as weight loss at 105 °C in an oven dryer (AACC 1993b). Concentrations of reducing sugars in the tubers were determined enzymatically in lyophilised samples according to Boehringer (1995), and detected at 365 nm by a U 1100 Spectrophotometer (Hitachi, Mannheim, Germany).

N, K and P-contents of tuber were analysed after freeze-drying according to the method described in VDLUFA (1997) using atomic absorption spectrometer (contrAA 300, Analytic Jena, Jena, Germany). Mineral elements were measured at time of harvest.

3.2.4 Statistical Analysis

Both experimental years were analysed separately, because in 2004 an additional defoliation system (1MU), as well as the slurry fertilization, were added to the study. All statistical analyses were carried out with Statistical Analysis Systems, version 9.1.3 (SAS Institute 2004) and significance was set at $\rho<0.05$. Analysis of variance was calculated with the procedure MIXED. Denominator degrees of freedom were approximated by the Kenward-Roger method (Kenward and Roger 1997). Residuals were checked for normal (Gaussian) distribution and homogeneity of variance with PROC UNIVARIATE. If necessary, data were log-, square-root- or arcsinus-transformed and subjected to analysis of variance. LSMEANS and their associated 95 % confidence limits means were transformed back to the original scale. The experiment was designed in 2003 as a two-factorial split-plot trial. Factors “defoliation system” (DS) and “cultivar” (CV) were combined in the fixed part of the mixed model. In 2004, the experiment was designed as a three-factorial split-plot trial. The factors “defoliation system” (DS) and “cultivar” (CV) were combined with the factor “slurry fertilization” (SF). For the parameters, which were also assessed after the 4-months storage period, the factor “storage” (STOR) was also included in the model. The replicate (REP) was combined with DS and treated as random effect (main plot error). In Tables 3.6, 3.8, 3.10 and 3.12, simple means are presented. The least significant differences (LSD) given at the bottom of each table are based on a full-factorial analysis and can be used for comparisons of means between two treatment factor levels at a given combination of the other factors. When factors shared the same LSD, the former are separated by a comma.

3.3 Results

3.3.1 Defoliation effects on ryegrass-clover shoot matter production

With the exception of the annual N-amount in 2002 and the total potentially harvestable shoot dry matter in 2003, there was a significant effect of the defoliation systems on all considered parameters of potentially harvestable shoot dry matter yield, percentage of clover and the annual N-amount (Table 3.4). The potentially harvestable yield shoot matter, clover shoot matter and annual N-amount from the cutting-systems (3C and 2C/1MU) were markedly higher in 2003 than in 2002 (Table 3.4). In both years, the 3MU-system led to the lowest potentially harvestable yield shoot matter, and there was a significant difference between the 3C- and 3MU-system in 2002. The 3MU-system led to a significantly higher potential harvestable yield of grass shoot matter and to a significant lower percentage of clover in comparison to the other variants. In both years, the annual N-amount was not significantly different by defoliation system, but the mulching-systems tended to result in lower values compared to the cutting-systems (Table 3.4). The additional 1MU-defoliation system in 2003 also resulted in a significantly lower annual N-amount. In addition, this variant had a comparably higher level of potential harvestable shoot matter of clover than the 3MU-system. The yield of grass shoot matter was significantly lower and the percentage of clover was significantly higher in the 1MU-system compared to the 3MU-system.

3.3.2 Defoliation effects on ryegrass-clover crop residues

The residues of the ryegrass-clover mixture are summarized as total residues (sum of shoots and roots) and are described by the parameters organic matter (OM), N-amount and C:N-ratio (Table 3.4). In 2002, OM and N-amounts were significantly higher in the 3MU-system compared to the cutting-systems. In 2003, however, this was not the case; the additional 1MU-system resulted in higher OM and significantly higher N-amount values. The C:N-ratios of crop residues were higher in 2002 than in 2003; however, there were no significant differences in defoliation systems between years.

3.3.3 Total Tuber Yield and Size-Graded yields

In 2003, the total tuber yield was significantly different by defoliation system and cultivar (Table 3.5). The 3MU-system resulted in highest total yields, followed by the pure cutting-system (3C) and the 2C+1MU-system (Table 3.6). The cv. Agria had a significantly higher total yield (36.3 t ha^{-1}) than cv. Marlen (32.4 t ha^{-1}). A significant effect of the defoliation system on size-graded yields was only observed for tubers of 50-60 mm, where the 3MU-system had the highest yields. The cultivar had a significant effect on all tuber size-fractions. For the size-fraction <40 mm and 40-50 mm, cv. Marlen had higher tuber yields, while for the proportion of tubers 50-60 mm and >60 mm, higher tuber yields were observed for cv. Agria.

In 2004, no significant differences in total yield were observed according to defoliation systems or cultivar (Table 3.5). Except for tuber yield of <40 mm, the cultivar had a significant influence on size-graded yields. 42 % of cv. Marlen´s and 40 % of cv. Agria´s total yields were of the 50-60 mm tuber fraction (Table 3.6). At the portion of tuber yield >60 mm, cv. Agria had significantly higher yields compared to cv. Marlen (Table 3.6). Significant interactions between defoliation system and cultivar were only observed for tuber yields 40-50 mm (Table 3.5). The pure cutting (3C) resulted in higher yields for both cultivars (Table 3.6). In all defoliation systems, cv. Marlen resulted in higher yields than cv. Agria, except of the 2C+1MU-system (Table 3.6).

Table 3.4: Effect of different defoliation systems (DS) on yield of potentially harvestable shoot dry matter, percentage of clover, annual N-amount of ryegrass clover and organic matter (OM), N-amount (N), and C:N-ratio of ryegrass-clover residues in autumn 2002 and 2003

Source of variation	Potentially harvestable yield of shoot dry matter (DM) (g m^{-2})						Percentage of clover		Annual N-amount		Crop residues					
	total		clover		grass		(%)		total (g N m^{-2})		OM (g N m^{-2})		N (g N m^{-2})		C:N	
2002																
3C	1293	a	980.6	a	312.7	b	75.7	a	37.2	a	481.1	b	13.6	b	20.8	a
2C+1MU	1255	ab	941.6	a	314.2	b	74.8	a	35.4	a	537.4	b	14.9	b	20.5	a
3MU	1083	b	701.9	b	381.5	a	64.9	b	30.0	a	874.4	a	22.3	a	21.5	a
2003																
3C	1478	a	1383	ab	94.2	b	93.5	a	43.2	a	565.6	a	16.4	b	17.9	a
2C+1MU	1510	a	1414	a	95.8	b	93.6	a	44.0	a	590.9	a	18.3	b	17.0	a
3MU	1377	a	1241	b	135.8	a	90.1	b	40.7	a	560.3	a	16.2	b	17.7	a
1MU	1388	a	1324	ab	83.7	b	95.4	a	30.3	b	833.5	a	25.2	a	17.7	a

Different lower case letters indicate significant differences between defoliation systems (tukey-test at ρ <0.05)

Table 3.5: Test of fixed effects: ρ-values for tests of sources of variations for yield and external quality traits of potato tubers for 2003 and 2004

Source of variation	Numerator df	Total Tuber FM yield	Tuber FM yield < 40 mm	Tuber FM yield 40-50 mm	Tuber FM yield 50-60 mm	Tuber FM yield > 60 mm
a) 2003						
DS	2	**0.0085**	0.4857	0.8645	**0.0382**	0.4033
CV	1	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
DS x CV	2	0.7665	0.1819	0.4333	0.5575	0.7017
REP	3	0.4766	0.8019	0.6262	0.1901	0.3517
b) 2004						
DS	3	0.8778	0.7240	**0.0233**	0.9507	0.3104
CV	1	0.1114	0.0908	**0.0009**	**0.0247**	**<.0001**
SF	1	0.2173	0.1393	0.2346	0.3327	0.8431
DS x CV	3	0.0598	0.0660	**0.0331**	0.7464	0.4987
DS x SF	3	0.0721	0.5663	0.3287	0.0844	0.1243
CV x SF	1	0.7765	0.2664	0.7709	0.4300	0.1604
DS x CV x SF	3	0.5678	0.6476	0.4049	0.1594	0.5190
REP	3	0.0244	0.3524	0.0011	0.0585	0.0071

ρ-values in bold represent significant effects at the 5% level

Table 3.6: Total tuber FM yield (t ha^{-1}) and graded fresh matter yields (t ha^{-1}) as affected by defoliation system (a+b) and cultivar (a+b) in the experimental seasons 2003 and 2004

		Total Tuber FM yield	Tuber FM yield < 40 mm	Tuber FM yield 40-50 mm	Tuber FM yield 50-60 mm	Tuber FM yield > 60 mm
a) 2003						
Defoliation System (DS)						
3C		34.10	3.97	11.35	10.20	4.32
2C + 1MU		32.97	4.38	12.16	9.14	3.27
3MU		35.60	3.92	11.70	11.23	4.70
Cultivar (CV)						
Agria		36.34	3.16	9.21	12.60	6.54
Marlen		32.36	5.01	14.27	7.77	1.65
LSD (5%)	DS	1.79	n.s.	n.s.	1.55	n.s.
	CV	1.46	0.46	1.21	1.27	1.61
b) 2004						
Defoliation System (DS)						
3C		31.59	2.53	10.66	12.68	4.07
2C + 1MU		30.79	2.43	8.56	12.91	5.05
3MU		30.53	2.38	9.75	12.38	4.37
1MU		30.34	2.51	9.06	12.46	4.37
Cultivar (CV)						
Agria		30.23	2.37	8.95	12.13	5.14
Marlen		31.41	2.55	10.07	13.09	3.79

n.s. = not significant

Table 3.6: continued

		Total Tuber FM yield	Tuber FM yield < 40 mm	Tuber FM yield 40-50 mm	Tuber FM yield 50-60 mm	Tuber FM yield > 60 mm
b) 2004						
Defoliation System	*Cultivar*					
3C	Agria	31.66	2.49	10.13	12.34	5.06
	Marlen	31.53	2.60	11.18	13.02	3.09
2C + 1MU	Agria	31.23	2.55	8.70	12.56	5.76
	Marlen	30.35	2.31	8.42	13.30	4.35
3MU	Agria	29.91	2.21	9.12	12.02	5.06
	Marlen	31.15	2.55	10.38	12.73	3.67
1MU	Agria	28.10	2.23	7.84	11.58	4.69
	Marlen	32.57	2.79	10.29	13.34	4.04
LSD (5%)						
	DS	n.s.	n.s.	1.27	n.s.	n.s.
	CV	n.s.	n.s.	0.63	0.83	0.61
	DS CV	n.s.	n.s.	1.48	n.s.	n.s.

n.s. = not significant

3.3.4 Dry Matter and Starch Concentrations of Tubers

Tuber DM and starch concentrations were higher in 2003 compared to 2004, and in both years, both were significantly higher in cv. Marlen than in cv. Agria. With the exception of starch concentration in 2003, a significant effect of the defoliation systems on DM and starch concentrations was observed in both years (Table 3.7). Compared to the 3C- and 2C+1MU-systems, the 3MU-system resulted in the lowest concentrations of both parameters. The additional 1MU-variant in 2004 did not differ significantly from the 3MU-system. In 2004, a defoliation system*cultivar interaction effect was observed. In cv. Marlen, significantly lower DM and starch concentrations were observed in the 1MU-system than in the 3MU-system when compared with cv. Agria. Storage as main effect had no significant impact on DM and starch concentrations, but there was a cultivar*storage interaction effect in 2003 (Table 3.7). Whilst both parameters significantly increased in cv. Agria, both significantly decreased in cv. Marlen. The further defoliation system*storage interaction effect in 2003 is based on the observation that starch concentrations at harvest, as well as after storage, were lower in the 3MU-system compared to the 3C- and 2C+1MU-systems, with a significant difference only between the 3MU- and 2C+1MU-system after storage (Table 3.8).

The additional slurry fertilization in 2004 resulted in a significant reduction in DM and starch concentrations (Table 3.8). The defoliation system*slurry fertilization interaction showed a significant decrease in starch concentrations in the 1MU-system, which had the lowest starch concentration compared to the other defoliation systems.

Table 3.7: Test of fixed effects: ρ-values for tests of sources of variation for internal quality traits of potato tubers for 2003 and 2004

Source of variation	Numerator df	Dry matter concentration (% in FW)	Starch concentration (% in FW)
a) 2003			
DS	2	**0.0345**	0.2623
CV	1	**<.0001**	**<.0001**
STOR	1	0.7845	0.1783
DS x CV	2	0.4237	0.0879
DS x STOR	2	0.1749	**0.0303**
CV x STOR	1	**0.0013**	**<.0001**
DS x CV x STOR	2	0.3828	0.5497
REP	3	0.4066	0.6915
b) 2004			
DS	3	**0.0021**	**0.0065**
CV	1	**<.0001**	**<.0001**
SF	1	**0.0002**	**0.0011**
STOR	1	0.8438	0.1880
DS x CV	3	**0.0180**	**0.0039**
DS x SF	3	0.0925	**0.0115**
DS x STOR	3	0.6162	0.6885
DS x CV x SF	3	0.4924	0.7056
DS x CV x STOR	3	0.6069	0.2087
DS x SF x STOR	3	0.6115	0.4588
CV x SF	1	0.4911	0.6110
CV x STOR	1	0.2949	0.6593
CV x SF x STOR	1	0.2660	0.4767
SF x STOR	1	0.5996	0.6593
DS x CV x SF x STOR	3	0.9698	0.8798
REP	3	0.0102	0.0345

ρ-values in bold represent significant effects at the 5% level

Table 3.8: Concentration of dry matter and starch in tubers at harvest and after storage as affected by defoliation system (a+b), cultivar (a+b) and slurry fertilization (b) in the experimental seasons 2003 and 2004

		Dry matter concentration (% in FW)		Starch concentration (% in FW)	
		At harvest	After storage	At harvest	After storage
a) 2003					
Defoliation System (DS)					
3C		26.94	26.74	21.53	21.48
2C + 1MU		27.16	27.56	21.54	22.03
3MU		26.59	26.25	21.19	21.13
Cultivar (CV)					
Agria		25.27	24.63	19.82	19.51
Marlen		28.52	29.07	23.02	23.58
		0.65		n.s.	
LSD (5%)	DS	0.34		0.19	
	CV	n.s.		0.84	
	DS STOR CV STOR	0.48		0.26	
b) 2004					
Defoliation System (DS)					
3C		23.99	24.04	20.05	20.19
2C + 1MU		23.57	23.71	19.63	19.89
3MU		23.17	23.09	19.49	19.55
1MU		23.10	22.91	19.30	19.29
Cultivar (CV)					
Agria		21.99	21.88	18.16	18.24
Marlen		24.92	25.00	21.08	21.85
Slurry Fertilization (SF)					
No		23.67	23.61	19.78	19.85
Yes		23.25	23.28	19.46	19.61

Table 3.8: continued

		Dry matter concentration (% in FW)		Starch concentration (% in FW)	
		At harvest	After storage	At harvest	After storage
b) 2004					
Defoliation System (DS)	*Cultivar (CV)*				
3C	Agria	22.40	22.40	18.52	18.56
	Marlen	25.59	25.69	21.59	21.82
2C + 1MU	Agria	21.93	22.15	17.90	18.41
	Marlen	25.21	25.28	21.36	21.38
3MU	Agria	21.71	21.38	18.00	18.02
	Marlen	24.63	24.81	20.99	21.08
1MU	Agria	21.94	21.58	18.22	17.95
	Marlen	24.26	24.24	20.38	20.63
Defoliation System (DS)	*Slurry Fert. (SF)*				
3C	No	24.21	24.25	20.26	20.28
	Yes	23.78	23.84	19.85	20.10
2C + 1MU	No	23.70	23.89	19.60	19.92
	Yes	23.44	23.54	19.67	19.87
3MU	No	23.16	23.13	19.48	19.67
	Yes	23.18	23.06	19.51	19.44
1MU	No	23.59	23.13	19.78	19.55
	Yes	22.61	22.69	18.82	19.03
LSD (5%)	DS	0.45		0.40	
	CV, SF	0.19		0.17	
	DS CV	0.50		0.45	
	DS SF	n.s.		0.45	

n.s. = not significant

3.3.5 Reducing Sugar Concentrations of Tubers

In 2003, reducing sugars (sum of glucose and fructose) were significantly higher in cv. Agria than in cv. Marlen, while in 2004, this was only the case for fructose. In addition, the sum of reducing sugars was lower in cv. Agria than in cv. Marlen in 2004 (Table 3.9, 3.10).

The defoliation systems as well as the additional slurry application in 2004 had no effects on reducing sugar concentrations. There was, however, a defoliation system*cultivar*slurry fertilization interaction effect (Table 3.9). Storage significantly increased reducing sugar contents in both years (Table 3.9), but this was more pronounced in 2004 (Table 3.10). In 2004, there was also a 4-way interaction effect on fructose concentrations (Table 3.9).

Table 3.9: Test of fixed effects: ρ-values for tests of sources of variations for glucose, fructose and the sum of the reducing sugars of potato tubers for 2003 and 2004

Source of variation	Numerator df	Glucose (g kg^{-1} FW)	Fructose (g kg^{-1} FW)	Glucose + fructose (g kg^{-1} FW)
a) 2003				
DS	2	0.8610	0.9404	0.9053
CV	1	**0.0094**	**0.0491**	**0.0186**
STOR	1	**<.0001**	**<.0001**	**<.0001**
DS x CV	2	0.7034	0.6393	0.6602
DS x STOR	2	0.9393	0.9476	0.9414
CV x STOR	1	0.4788	0.1403	0.7055
DS x CV x STOR	2	0.9023	0.9655	0.9636
REP	3	0.9131	0.9121	0.9249
b) 2004				
DS	3	0.1766	0.2554	0.2121
CV	1	0.6243	**0.0001**	0.0591
SF	1	0.4191	0.5929	0.4782
STOR	1	**<.0001**	**<.0001**	**<.0001**
DS x CV	3	**0.0086**	**0.0169**	**0.0101**
DS x SF	3	0.2717	0.1660	0.2196
DS x STOR	3	0.2863	0.0887	0.1784
DS x CV x SF	3	0.0640	**0.0255**	**0.0412**
DS x CV x STOR	3	0.0992	0.0873	0.0890
DS x SF x STOR	3	0.2801	0.2997	0.2822
CV x SF	1	0.9788	0.8310	0.2196
CV x STOR	1	0.8138	0.1995	0.5086
CV x SF x STOR	1	0.7195	0.7186	0.9409
SF x STOR	1	0.1618	0.3935	0.2309
DS x CV x SF x STOR	3	0.0997	**0.0368**	0.0662
REP	3	0.0269	0.0390	0.0311

ρ-values in bold represent significant effects at the 5% level

Table 3.10: Concentration of glucose and fructose in tubers at harvest and after storage as affected by cultivar (a+b), defoliation system and fertilization (b) in the experimental seasons 2003 and 2004

		Glucose (g kg^{-1} FW)		Fructose (g kg^{-1} FW)		Glucose + fructose (g kg^{-1} FW)	
		At harvest	After storage	At harvest	After storage	At harvest	After storage
a) 2003							
Cultivar (CV)							
Agria		0.11	0.18	0.02	0.11	0.13	0.29
Marlen		0.08	0.16	0.02	0.08	0.09	0.23
LSD (5%)	CV, STOR	0.019		0.018		0.036	
b) 2004							
Cultivar (CV)							
Agria		0.19	0.74	0.03	0.47	0.23	1.20
Marlen		0.20	0.76	0.08	0.56	0.28	1.32
Defoliation System	*Cultivar*						
3C	Agria	0.21	0.75	0.03	0.49	0.24	1.24
	Marlen	0.23	0.98	0.01	0.72	0.33	1.69
2C + 1MU	Agria	0.24	0.86	0.04	0.52	0.28	1.38
	Marlen	0.19	0.63	0.07	0.46	0.26	1.09
3MU	Agria	0.16	0.63	0.02	0.40	0.18	1.03
	Marlen	0.16	0.70	0.06	0.53	0.22	1.23
1MU	Agria	0.16	0.71	0.03	0.45	0.18	1.16
	Marlen	0.21	0.72	0.09	0.53	0.29	1.25

n.s. = not significant

Table 3.10: continued

b) 2004			Glucose (g kg^{-1} FW)		Fructose (g kg^{-1} FW)		Glucose + fructose (g kg^{-1} FW)	
Defoliation System	*Cultivar*	*Slurry Fert.*	At harvest	After storage	At harvest	After storage	At harvest	After storage
3C	Agria	No	0.19	0.76	0.04	0.48	0.23	1.24
		Yes	0.22	0.74	0.03	0.51	0.25	1.25
	Marlen	No	0.24	1.21	0.10	0.89	0.33	2.09
		Yes	0.23	0.75	0.09	0.55	0.32	1.29
2C + 1MU	Agria	No	0.25	0.84	0.03	0.51	0.28	1.35
		Yes	0.23	0.87	0.05	0.54	0.28	1.41
	Marlen	No	0.20	0.62	0.07	0.45	0.27	1.07
		Yes	0.18	0.64	0.06	0.47	0.24	1.11
3MU	Agria	No	0.11	0.70	0.01	0.42	0.12	1.12
		Yes	0.20	0.57	0.03	0.37	0.23	0.94
	Marlen	No	0.14	0.66	0.05	0.51	0.19	1.17
		Yes	0.18	0.75	0.07	0.55	0.25	1.30
1MU	Agria	No	0.16	0.79	0.03	0.49	0.19	1.28
		Yes	0.16	0.63	0.02	0.42	0.18	1.04
	Marlen	No	0.19	0.64	0.08	0.47	0.27	1.11
		Yes	0.22	0.79	0.09	0.60	0.32	1.39
LSD (5%)	CV		n.s.		0.035		n.s.	
	STOR		0.054		0.035		0.088	
	DS CV		0.014		0.099		0.024	
	DS CV SF		n.s.		0.024		0.029	
	DS CV SF STOR		n.s.		0.154		n.s.	

n.s. = not significant

3.3.6 Nitrogen Concentrations of Tubers

In 2003, the defoliation system and cultivar had no significant effect on N concentrations. In 2004, a significant cultivar and fertilization effect was observed. N was significantly higher in cv. Agria, and after slurry fertilization (Table 3.11).

A 3-way defoliation system*cultivar*slurry fertilization interaction was also observed (Table 3.11). The additional slurry fertilization led to the highest N concentrations, especially in cv. Agria (Table 3.12).

3.3.7. Mineral Elements (K, Mg, P) Concentrations of Tubers

In both years, cultivars did not significantly differ in potassium (K) concentrations (Table 3.11). In 2003, K was not significantly affected by defoliation system, but mulching as well as the additional slurry fertilization significantly increased K in 2004. Furthermore, a significant defoliation system*cultivar interaction effect, as well as defoliation system*slurry fertilization interaction effect, were observed (Table 3.11). The pure mulching-system led to significantly higher tuber K concentrations in cv. Marlen. Highest K values were measured in the additional fertilized tubers from the 1MU-system and in the 3MU-system (Table 3.11). In both years, magnesium (Mg) concentrations were significantly higher in cv. Marlen than in cv. Agria (Tables 3.11, 3.12). Phosphorous (P) concentrations were not different between cultivars in 2003, but in 2004, were significantly higher P concentrations were found in cv. Agria than in cv. Marlen. The defoliation system and slurry fertilization had no effect on Mg and P concentrations.

Table 3.11: Test of fixed effects: *ρ*-values for tests of sources of variations for nitrogen and the mineral elements in the tubers for 2003 and 2004

Source of variation	Numerator df	N (g kg^{-1} DM)	K (g kg^{-1} DM)	Mg (g kg^{-1} DM)	P (g kg^{-1} DM)
a) 2003					
DS	2	0.6933	0.2807	0.2916	0.2215
CV	1	0.3090	0.9113	**0.0423**	0.4846
DS x CV	2	0.2694	0.5987	0.3686	0.8391
REP	3	0.3883	0.1847	0.0566	0.5814
b) 2004					
DS	3	0.8773	**0.0174**	0.0534	0.8246
CV	1	**<.0001**	0.3613	**0.0025**	**<.0001**
SF	1	**<.0001**	**<.0001**	0.0974	0.1241
DS x CV	3	0.9633	**0.0004**	0.5436	0.9811
DS x SF	3	0.7640	**0.0328**	0.5268	0.1111
CV x SF	1	0.4170	0.7070	0.8079	0.6136
DS x CV x SF	3	**0.0236**	0.2386	0.2723	0.4583
REP	3	0.3413	0.0882	0.2864	0.1319

ρ-values in bold represent significant effects at the 5% level

Table 3.12: Concentration of nitrogen, potassium, magnesium and phosphorous in tubers at harvest as affected by cultivar (a+b), defoliation system (b) and slurry fertilization (b) in the experimental seasons 2003 and 2004

		N (g kg^{-1} DM)	K (g kg^{-1} DM)	Mg (g kg^{-1} DM)	P (g kg^{-1} DM)
a) 2003					
Cultivar (CV)					
Agria		11.6	19.05	0.98	2.06
Marlen		12.0	19.14	1.06	2.01
LSD (5%)	CV	n.s.	n.s.	0.08	n.s.
b) 2004					
Defoliation System (DS)		10.6	17.92	0.95	2.12
3C		10.6	17.89	0.99	2.13
2C + 1MU		10.5	19.37	1.04	2.07
3MU		10.6	20.14	1.01	2.07
1MU					
Cultivar (CV)		10.9	18.98	0.97	2.19
Agria		10.2	18.68	1.03	2.00
Marlen					
Slurry Fertilization (SF)		10.2	15.90	1.01	2.13
No		11.1	21.76	0.98	2.07
Yes					
Defoliation System (DS)	*Cultivar (CV)*				
3C	Agria	11.1	18.33	0.93	2.22
	Marlen	10.2	17.50	0.97	2.02
2C + 1MU	Agria	11.0	19.20	0.96	2.22
	Marlen	10.3	16.59	1.01	2.04
3MU	Agria	10.8	18.97	0.98	2.22
	Marlen	10.2	19.77	1.09	1.99
1MU	Agria	11.0	19.41	0.99	2.17
	Marlen	10.3	20.86.	1.04	

n.s. = not significant

Table 3.12: continued

			N (g kg^{-1} DM)	K (g kg^{-1} DM)	Mg (g kg^{-1} DM)	P (g kg^{-1} DM)
b) 2004						
Defoliation System	*Slurry Fert.*					
3C	No		10.2	14.29	0.96	2.22
	Yes		10.9	21.58	0.94	2.02
2C + 1MU	No		10.2	15.65	0.99	2.11
	Yes		11.0	20.13	0.98	2.15
3MU	No		10.2	16.47	1.04	2.07
	Yes		10.8	22.27	1.03	2.08
1MU	No		10.1	17.22	1.05	2.10
	Yes		11.2	23.06	0.98	2.03
Defoliation System	*Cultivar*	*Slurry Fert.*				
3C	Agria	No	11.1	15.04	0.97	2.36
		Yes	11.1	21.63	0.89	2.08
	Marlen	No	9.4	13.46	0.96	2.08
		Yes	10.9	21.54	0.98	1.97
2C + 1MU	Agria	No	10.5	16.42	0.97	2.17
		Yes	11.4	21.97	0.95	2.26
	Marlen	No	9.9	14.89	1.02	2.06
		Yes	10.7	18.29	1.01	2.03
3MU	Agria	No	10.6	16.18	0.96	2.12
		Yes	11.0	21.76	1.01	2.20
	Marlen	No	9.7	16.76	1.12	2.01
		Yes	10.6	22.78	1.05	1.96
1MU	Agria	No	10.2	16.31	1.03	2.19
		Yes	11.8	22.52	0.96	2.15
	Marlen	No	10.0	18.13	1.08	2.02
		Yes	10.56	23.59	0.99	1.91
LSD (5%)		DS	n.s.	1.48	n.s.	n.s.
		CV	0.03	n.s.	0.04	0.07
		SF	0.03	0.66	n.s.	n.s.
		DS CV, DS SF	n.s.	1.67	n.s.	n.s.
		DS CV SF	0.08	n.s.	n.s.	n.s.

3.4 Discussion

3.4.1 Defoliation effects on ryegrass-clover shoot matter production and ryegrass-clover crop residues

In the present study, the cutting-systems (3C and 2C+1MU) resulted in a relatively higher annual potential harvestable total shoot matter and annual N-amount than the mulching-systems. This observation is in good agreement with the studies of Loges (1998), Heuwinkel et al. (2002) and Dreymann (2005), who analysed yield and N-amount of red clover and red clover-grass. According to Frame et al. (1998) and Loges (1998), this could be explained by an inhibition of the regrowth of new shoots, growth by shading, and phytotoxicity of the remaining mulching material. In the current study, mulching also increased the grass and reduced the clover fraction, especially observed in the 3MU-system in both experimental years. This was also described by Dreymann (2005). An explanation could be that the N-mineralization of the remaining mulching material by microorganisms led to a rise of available N. Due to the higher N-appropriation capacity of grass compared to clover (Høgh-Jensen et al. 1997), the N-accumulation promoted grass growth, which resulted in a decline of the clover fraction. It is remarkable that notably higher grass fractions were found in 2002 when compared to 2003. This can be explained by the fact that in 2002, the ryegrass-clover struggled to grow through the winter and additional grass was reseeded with a grassland-drilling machine. The higher grass fractions resulted from the 30 % of plants from the gap-filling reseeding. The higher clover fractions in 2003 can also be explained by the prevailing weather conditions. The deeply rooted red clover suffered less from dryness than the level-being rooted grass. The higher percentage of clover, almost pure clover crop in 2003, compared to 2002 may explain the significantly lower C:N-ratio of the residues in 2003 (Table 3.4).

3.4.2 Total Tuber Yield and Size-Graded yields

In this study, an average tuber yield of 34.4 t ha^{-1} was obtained for all cultivars and defoliation systems in 2003 compared to 30.8 t ha^{-1} in 2004. This might be explained with the prevailing weather conditions in both years. Especially in 2004, the higher precipitation amounts, as well as an early infection and resulting damage by *P. infestans*, led to an early interruption of yield formation. According to the *Federal Office of Plant Varieties* (Bundessortenamt 2004), cv. Agria is assigned to the stem-type of potatoes, while cv. Marlen is assigned to the intertype, with a trend towards leaf-type. With increasing dry stress, the stem-type potato with its high herbal matter can have a yield advantage compared to the leaf-type. The leaf-type, cv. Marlen, profits from years with sufficient water supply, like observed in the current study in 2004 (Schittenhelm et al. 2006). Due to the dry summer in 2003 and the specific morphological features of the two different potato cultivars, cv. Agria had a yield advantage of 12 % compared to cv. Marlen. The highest amount of OM of the crop residues from the 3x mulching ryegrass-clover fields in 2002 may have influenced the retaining capacity of the soil and thus resulted in higher total tuber yields in 2003. In 2004, the total yield was not significantly affected by the different systems and cultivars (Table 3.6). Due to the greater annual precipitation in that year neither cultivar suffered from water deficiency. Böhm et al. (2002) reported comparably high yields of cvs Agria and Marlen. That there was no significant effect of the defoliation system on yield in 2004 could be explained by the fact that there were no differences in the OM and N-amounts or in the total annual N-amount of the crop residues of the cutting-systems (3C and 2C+1MU) and the 3MU-system. The 1MU-system resulted in higher N-amounts of the crop residues, but in lower annual N-amounts, so that in summation this did not result in higher yields. Dreymann (2005) conducted a two-year study with different grass-clover defoliation systems and did not find a significant effect on winter wheat yields. In addition, they (Dreymann 2005) studied the effect of different seed mixtures on winter wheat yield and found that a 100 % red-clover seed-mixture and 67 % red-clover + 33 % rye grass seed-mixture resulted in a yield advantage for the 2C+2MU-system compared to the 3C+1MU- and the 4MU-system.

In order to make cultivation of potatoes for processing into crisps more profitable, the tuber yield fraction in the size grade 40-65 mm should be maximised (Schuhmann 1999). On average for all defoliation systems and cultivars, the fraction of marketable wares >40 mm was 75.6 % in 2003 and 86.2 % in 2004.

As demonstrated for the total yield, the cultivars had also a significant effect on the tuber size distribution. This can be explained by the specific morphological features of both cultivars and the different weather conditions in both years. In cv. Marlen (reference cultivar for crisps) the portions of tuber yield >50 mm was 28.9 % of total yield in 2003 in contrast to 53.6 % in 2004. Using cv. Agria (reference cultivar for French fries) these proportions were 52.6 % and 56.9 %, respectively. These results are in accordance with Haase et al. (2007b), who reported that cultivars had a main effect on tuber yields graded for crisp and French fries production.

Additional slurry fertilization in 2004 did not significantly affect total tuber yield or size-graded yields. This could be explained by either the high N status of the soil (Stein-

Bachinger and Werner 1997) or poor mineralization of N from manure (Neuhoff and Köpke 2002; Haase et al. 2007b). According to Neuhoff et al. (1997), an increase of fertilization with farmyard manure increased tuber weight, also leading to an increased proportion of larger tuber size. Böhm and Dewes (1997) showed that there was a decrease of undersized tubers and an increase of oversized tubers with raising manure fertilization. Stein-Bachinger and Werner (1997) found that higher N-application rates increase the percentage of large tubers. According to Haase et al. (2007b), the lack of response of graded tuber yields to fertilization with cattle manure, as in our study, can be explained by the poor or late mineralization of N. In addition, an early infestation with *P. infestans* can influence the yield (Matthies 1991) and size-graded yield-formation (Haase et al. 2007b). Haase et al. (2007b) found an increase of marketable yields for the potato processing industry in years with or without *P. infestans*. This is also evident in our study, especially for cv. Agria.

3.4.4 Dry Matter and Starch Concentrations of Tubers

Dry matter concentration of tubers is a very important quality parameter of processing potatoes used for French fries and crisps (Schuhmann 1999). High DM concentrations result in higher yields of crisps and reduced crisp oil concentrations (Lulai and Orr 1979). Tuber DM concentration has been shown to be cultivar-specific and to be dependent on weather conditions, especially sunshine duration, temperature and precipitation (Kolbe 1990). The high sunshine duration as well as the warm and dry weather conditions might be a reason for the higher DM concentrations observed in 2003 when compared to 2004. The time period for DM accumulation was extended due to the infestation with *P. infestans* in 2003. In addition to climatic conditions, tuber DM concentrations are genetically predetermined (Stanley and Jewell 1989). In the present study, we also found in cv. Marlen (reference cultivar for crisps) higher DM concentration in comparison to cv. Agria (reference cultivar for French fries) (Tables 3.8). In both years, the DM concentrations in both cultivars met or exceeded the minimum range of 21-25 % for crisps (cv. Marlen – 2003: 28 %, 2004: 25 %) and 19-23 % for French Fries (cv. Agria – 2003: 25 %, 2004: 22 %).

In both years, mulching caused lower tuber DM concentrations than the two other defoliation systems. In 2004, this was more pronounced in cv. Agria, which is characterized by lower genetically predetermined DM concentrations as compared to cv. Marlen. The higher N contents of the crop residues in exclusively mulched systems might lead to a better N-supply resulting in a decrease of tuber DM concentration. In accordance with this, we observed a significant decrease of DM concentrations from 23.7 to 23.3 %

in FW after slurry application in 2004. This is in good agreement with previous studies: Guarda et al. (1994), Böhm and Dewes (1997), Schulz et al. (1997) and Thybo et al. (2001) found a continued decrease of DM concentration as organic fertilization increased. In 2003, we found a 2-way interaction between cultivar and storage, whereby we observed a slight but significant increase in DM concentrations in cv. Marlen, which also tended to result in 2004. Haase et al. (2007a) suggested that the increase in tuber DM concentrations results from water loss due to transpiration, which was higher than the losses of DM by respiration. They (Haase et al. 2007a) also analysed the effect of agronomical measures on selected quality parameters, such as starch, as well as condition of cvs Marlen and Agria at harvest and after storage, but found no significant interaction between cultivar and storage. Kolbe et al. (1995) observed that tubers from plants receiving high N had lower DM concentrations after storage when compared to at harvest, which conflicts with present results (Table 3.8).

Starch is the main component of DM (Kolbe 2003). Hence, there is a positive correlation between starch and DM concentrations (Müller and Cervenkova 1978). Compared to 2004, tubers in 2003 had more time to mature and synthesise starch due to the longer sunshine period, the warm and dry weather conditions, as well as low intensity of infestation with *P. infestans*. In both years, the higher starch concentrations in tubers of cv. Marlen (16-20 %) compared to cv. Agria (14-18 %) can be explained by genetic characteristics.

In addition, tubers from the cutting systems were characterized by higher starch concentrations in both years. The cut-used defoliation systems differed markedly in terms of starch enrichment in 2004, and especially so in cv. Marlen. This phenomenon may be explained by lower N supply of the cutting management, which led to an increase in starch concentrations.

We observed a significant interaction between N supply by slurry fertilization and type of defoliation system. The lowest starch concentrations were measured in the fertilized tubers from the pure mulching-systems (3MU and 1MU). It can be suggested that the high N supply in the soil by mulching and fertilization may be the reason for the lower starch concentrations in these systems. The fertilization seemed to have a greater influence on starch concentrations compared to the defoliation systems. This is in good agreement with Haase (1992), Neuhoff et al. (1997), Schulz et al. (1997) and Möller and Kolbe (2003), who observed a decrease of starch concentrations after applying organic fertilizer (Table 3.8).

In our study, storage led to an increase in starch concentrations in cv. Marlen (+3 %) and to a slight decrease in cv. Agria (-2 %) in 2003. The concentrations of both cultivars were slightly above the required threshold minimum of 22 % (cv. Marlen) and 19 % (cv. Agria) (Table 3.8). A reduction in starch concentrations after storage, i.e., starch saccharification, was reported by Amir et al. (1977); however, we observed higher starch concentrations in tubers from the cutting variants (3C and 2C+1MU) after storage. This may be due the higher N-amounts in our variants that were partially removed from the fields (Table 3.4). Indeed, it has been reported that an increase of N-supply is accompanied by a decrease in starch concentrations (Kolbe 1990).

3.4.5 Reducing Sugar Concentrations of Tubers

The level of reducing sugars in potato tubers is an important factor influencing processing quality, especially the colour of the frying product (Roe and Faulks 1991; Putz and Lindhauer 1994). Sugar levels are influenced by several factors, including genotype, environmental conditions and cultural practices during growth, as well as several post-harvest factors such as storage (Kumar et al. 2004).

According to Cunningham and Stevenson (1963) and Stevenson et al. (1964), the heritable trait influenced the amount of total sugar concentrations. In our study, there are conflicting results. In 2003, cv. Marlen was characterized by lower sugar concentrations than cv. Agria, while in 2004, the reverse was true (Table 3.10). In both years, the sugar concentrations in both cultivars were markedly beneath the threshold.

In the two experimental years the prevailing weather conditions had a decisive influence on the sugar concentrations. Moll (1967) and Smith (1975) found out that soil moisture can affect the resulting sugar accumulation in fresh harvested tubers. Due to the higher precipitation levels in 2004, it came to moistly soils and steadily infestation with *P. infestans*, the maturation was interrupted and a physiological maturity could not occur. In accordance with Putz and Gehse (1975) dry and warm weather conditions, like in our study 2003, result in lower sugar concentration. The stage of maturity at lifting has a large effect on the storage potential (Kumar et al. 2004). According to Grassert et al. (1984) and Davies et al. (1989) tubers that suffered under drought during growth had a lower increase of reducing sugar contents, while moisture stress during or after flowering caused a high increase reducing sugar accumulation during storage (Owings et al. 1978). This was also observed in our study.

In numerous studies it could be shown that high N application rates (>150 kg N ha^{-1}) affect reducing sugar concentration (Swiniarski and Ladenberger 1970; Roe et al. 1990; Kolbe et al. 1995). Haase et al. (2007a) did not find any significant response of reducing sugars to preceding crops and slurry fertilization in their factorial field experiments. Their data (Haase et al. 2007b; 2007c) indicated that the usually high supply of available N will not be achieved in organic potato cropping. Stricker (1974) found that N-supply has only a limited effect on sugar concentrations. This is in good agreement with our results. In the present investigation additional fertilization in 2004 with 75 kg N_t ha^{-1} of slurry had a significant effect on only the 3-way interaction. With the exception of cv. Agria from the 3C-variant, the fertilized tubers from the cutting-management systems (3C and 2C+1MU) showed lower tuber concentrations of total reducing sugars (Table 3.10). Possibly the used cattle manure, which is characterized by high potassium amounts (Peretzki and Heigl 2004) had an impact on the reducing sugar accumulation. In our study this is supported by the higher tuber K concentrations after fertilization (see section mineral elements (K, Mg, P) concentrations of tubers). According to Westermann et al. (1994) mineral K application resulted in lower reducing sugar concentrations. These results confirm the statement of Putz and Gehse (1975) and Hunnius (1977) as well as Putz and Lindhauer (1994), that the influence of a balanced fertilization on reducing sugars concentration is minor compared to the influences of cultivar, year and location.

Storage led to an increase of sugar concentration in both years. In 2003, an increase of about 100 % was seen, and in 2004, the year with already higher sugar concentrations due to the early infestation with *P. infestans*, more than 600 % increase was measured (Table 3.11). The results support the investigations of Putz and Lindhauer (1994), who showed that immature tubers resulted in an increase in reducing sugar values by over 400 % in the first four weeks of storage.

Overall can be concluded that the required thresholds of a maximum of 2.5 g kg^{-1} FW reducing sugars for French fries processing were not exceed in both years. In 2004, tubers from the cut-used variant Marlen had with 2.1 g kg^{-1} FM reducing sugar concentration above the required maximum of 1.5 g kg^{-1} for crisps.

3.4.6 Nitrogen Concentrations of Tubers

On average higher N concentrations in tubers were measured in 2003 compared to 2004. These differences in tuber N concentrations could be explained with the different prevailing weather conditions in both years. Rising daily average temperatures (May-August), such as in 2003, lead to an increase in the levels of organic N compounds in the tubers. Precipitation values above 50 mm per month, as in 2004, lead to a decrease of N compounds in the tubers due to the increased dislocation and leaching of soil-N based on increasing water saturation (Kolbe 1990).

The different defoliation systems were significant in combination with cultivar and the additional fertilization. The interaction results indicated that independent of cultivar and defoliation system, slightly, or even significantly, higher N concentrations were found in fertilized tubers. The results suggest that the influence of cultivar and defoliation system is minor compared to the influence of fertilization. This is in good agreement with results of Millard (1986), who showed that increasing nitrogen fertilization led to an increase of nitrogen concentration in tuber dry matter. For grain, slightly higher nitrogen contents due to mulching were described by Dreymann (2005).

3.4.7 Mineral Elements (K, Mg, P) Concentrations of Tubers

Mineral elements contribute to specific processing qualities (discolouration) and are essential for human nutritional quality (Pawelzik 2000). Levels of mineral in the tuber have been proven to depend mainly on weather conditions, especially sunshine duration, temperature and precipitation (Kolbe 1990). The observation of Kolbe (1990) that high sunshine durations, as well as warm and dry weather conditions, as in 2003, lead to higher mineral uptake in the tubers can only confirmed in the present study for K and Mg. The higher K concentrations in tubers from the mulching fields may be explained with the high K contents in red clover and ryegrass. According to Hartmann and Sticksel (2010), K-removal of ryegrass-clover is about 350 kg K ha^{-1}. In the case of mulching the ryegrass-clover, a high amount of K is available for succeeding crop potatoes.

Markedly higher K concentrations were measured in fertilized tubers from the pure mulching fields (Table 3.12). The fertilized potatoes from the 1MU-fields had 62.1 % higher K-contents compared to the unfertilized tubers from the 3C-defoliation system. This is in good agreement with the results of Meineke (1994), as well as, Böhm and Dewes (1997), who found an increase of tuber K concentration after increased organic fertilization. In this study, in addition to the nutritional effect of the mulching material, also the nutrient effect of the slurry, which is in particular rich in K, has a positive effect on K concentration. With 56 mg K kg^{-1} and 73 mg K kg^{-1} respectively, K contents of the site were only moderate (Table 3.3) and so a sufficient K supply has to be ensured. The additional mineral K-fertilization with 120 kg K_2O ha^{-1} may have an influence on tuber K concentration, too. According to the nutritional information panel for table potatoes (Souci et al. 2008), the K concentration in tuber DM in the present study was within the average of all values in the upper range. This is in good agreement with the results of Meineke (1994).

In both years cv. Marlen showed significantly higher Mg concentrations compared to cv. Agria (Table 3.12). Higher P concentrations were detected in cv. Agria compared to cv. Marlen. This was significant in 2004. According to Spiegel and Sager (2008), a possible reason for the cultivar differences in element assimilation could be that the availability is higher than the specific mobility of genotype within the plant. The influence of genotype has no effect if the availability is too low or the mobility within the plant is too high.

On average the P concentration in tubers was in the lower third of the so-called normal range specified by Souci et al. (2008). Mg concentration was beneath the values of the nutritional information panel (Souci et al. 2008). Mg as well as P concentrations were in the same range described by Meineke (1994).

3.5 Conclusions and Perspectives

The aim of the investigation was to examine whether different defoliation systems (cutting, mulching and a combination of cutting and mulching) of the pre-crop ryegrass-clover had an effect on selected quality attributes of organically grown potatoes, destined for processing into French fries (cv. Agria) or crisps (cv. Marlen). In 2003, total tuber yield and the fraction of marketable wares 50-60 mm were significantly increased by the pure mulching-system; in 2004, size graded yields 40-50 mm was significantly increased by the pure cutting-system. The application of slurry fertilizer in 2004 with 75 kg N_t ha^{-1} had no significant influence on total tuber and size-graded yields as well as on reducing sugars, however, for DM and starch concentrations a decrease, and for N and K concentrations an increase, were observed. The different weather conditions in both years in combination with the potato genotype and its different morphological features had a great influence on total yields, size-graded yields and quality. The required size-grade of >35 mm with a proportion of at least 60 % of tubers >50 mm of the *organic* French fries industry, was with 52.6 % (2003) and 56.9 % (2004) nearly reached. Due to the limit fertilizer use in organic farming compared to conventional potato production, it will be difficult for the potato growers to meet these requirements without sorting out the small tubers. Therefore, it is important to keep cultivation measures, like plant spacing, irrigation and fertilization alternatives. In 2003, both cultivars reached good processing qualities. The increase in reducing sugar contents during storage in 2004 led to a deterioration of quality, the maximum threshold of 1.5 g kg^{-1} FW for crisps processing were exceeded, indicating that storage conditions have to be improved.

Because only in 2003 mulching had a minor yield advantage, the cutting-system appears to be meaningful, also for the farmers without livestock. Growth could be used in biogas plants, resulted digestates can be re-deployed to the farms fields. Furthermore, cooperation with livestock farms using the cutting clover grass as fodder and in return make manure or slurry available to the cropping farmers.

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4 The influence of volatile compounds on the flavour of raw, boiled and baked potatoes: Impact of agricultural measures on the volatile components

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Zusammenfassung

Der Einfluss flüchtiger Verbindungen auf das Aroma roher, gekochter und gebackener Kartoffeln: Einfluss agronomischer Maßnahmen auf die flüchtigen Verbindungen

In dem Beitrag werden die Entstehungswege flüchtiger Verbindungen in rohen, gekochten und gebackenen Kartoffeln dargestellt und deren Bedeutung für das Kartoffelaroma aufgezeigt. Des Weiteren wird der Einfluss agronomischer Maßnahmen, wie Sortenwahl, Düngung und Lagerung, als auch der Einfluss verschiedener Zubereitungsmöglichkeiten (Backofen, Mikrowelle) auf die Bildung flüchtiger Verbindungen herausgearbeitet.

Der Erfolg eines Lebensmittels ist abhängig von einem positiven, im englischen mit „Flavour“ bezeichneten Aroma. Das Aroma wird hervorgerufen durch flüchtige Verbindungen, die durch metabolische Prozesse in der Pflanze bzw. durch den weiteren Verarbeitungsprozess entstehen. Für das Aroma gekochter bzw. gebackener Kartoffeln sind besonders die thermischen Einflüsse, die während der Zubereitung auf die Kartoffel einwirken, von ausschlaggebender Bedeutung. Eine Vielzahl von Reaktionsprodukten ist die Folge. Auf Basis der durchgeführten Literaturrecherche wird gezeigt, dass bislang 159 flüchtige Verbindungen in rohen Kartoffeln, 182 in gekochten sowie 392 Aromastoffe in gebackenen Kartoffeln identifiziert wurden.

Das Aroma roher bzw. verarbeiteter Kartoffeln ist zum einen sortenspezifisch, d.h. genetisch festgelegt, aber auch Standort, Düngung, Lagerung, sowie Verarbeitung haben einen Einfluss auf die Bildung flüchtiger Verbindungen und können somit die sensorische Qualität beeinflussen. Obwohl umfassend belegt ist, dass insbesondere die Düngung und die Lagerung einen deutlichen Einfluss auf die Inhaltsstoffe der Kartoffel haben, gibt es bislang nur wenige Arbeiten, in denen die Auswirkungen unterschiedlicher Bewirtschaftungsmaßnahmen auf die Entstehung und die Zusammensetzung flüchtiger

Verbindungen untersucht wurden.

Hieraus wird deutlich, dass zukünftig ein hoher Forschungsbedarf hinsichtlich des Einflusses agronomischer Maßnahmen auf flüchtige Aromastoffe und damit auf die sensorische Qualität von Kartoffeln besteht. Durch den Vergleich von Aromastoffen in rohen und zubereiteten Kartoffeln könnte auf positive bzw. negative Einflüsse von Roh- auf Endproduktaroma geschlossen werden. Diese Informationen könnten in der Züchtung genutzt werden, um Sorten mit bestimmten, den Konsumentenwünschen entsprechenden sensorischen Qualitäten zu etablieren.

Schlüsselwörter: Kartoffel, Aroma, Flüchtige Verbindungen, agronomische Maßnahmen, Zubereitungsbedingungen

Abstract

The article deals with the development and identification of volatile compounds in raw, boiled and baked potatoes and their relevance for potato flavour. It outlines the influence of agronomic measures, such as the choice of variety, fertilization and storage, as well as the influence of diverse preparation possibilities (ordinary oven, microwave) on the formation of volatiles.

The success of a food depends on its positive flavour. Flavour is created by aromatic volatile compounds that are biosynthesized in the plant during metabolic processes and further modified by cooking or processing. Especially the thermal impacts during the preparation process are of decisive importance and responsible for the boiled and baked potato flavour. Multiplicities of reaction products are the consequence. Based on the literature research, there were 159 volatiles identified in raw potatoes, 182 in boiled and 392 in baked potatoes.

The flavour of raw, respectively processed, potatoes is variety specific, which means genetically defined. But the natural habitat determinants, the fertilization, storage conditions as well as the processing also have an influence on the forming of volatile compounds and could therefore affect the sensory quality. Although it is scientifically documented that particularly the fertilization and the storage conditions have an influence of the potato ingredients, there are hardly findings concerning volatile compounds in this context.

This stresses the future need for research, in particular regarding the effects of agronomic measures on the volatile compounds and sensory quality of raw as well as processed potatoes. By comparing the volatiles of raw potatoes with those of processed potatoes, positive or negative impacts by the raw product on the final product- flavour could be determined. This information could serve for breeding new varieties with certain properties, which eventually comply with consumer demand.

Keywords: Potato, Flavour, Volatile compounds, Agricultural measures, Preparation conditions

4.1 Introduction

Potatoes (*Solanum tuberosum L.*) are the world's most popular vegetable, a source of many essential nutrients and rich in vitamin C, potassium, and other vital nutrients. The annual world production of potatoes is around 300 million tons, and areas planted cover more than 18 million hectares (Cipotato 2008). The secret of the potato's success is its great diversity in colours, textures and tastes (FAO 2008). One more reason for its vast popularity is that the tuber can be prepared in a number of different ways, including simple boiling, baking, deep-fat frying and dehydration. It's relatively neutral and bland, yet characteristic, flavour is another reason for the wide acceptance of the potato (Maga 1994). The flavour of a food is created by aromatic chemicals that are biosynthesized during normal metabolic processes in plants and animals, and possibly further modified by cooking or processing (Reineccius 1999). Finally, human perception of flavour is influenced by numerous psychological and cultural factors (Jones 2008).

This review concerns the formation and significance of the various volatile compounds that have been identified in raw, boiled and baked potatoes and the influence of agronomic conditions like cultivar, fertilization, storage and different kinds of preparations on the forming of the flavour compounds.

Due to the widespread popularity of the potato, former potato flavour reviews exist (Self 1967; Johnson et al. 1971; Solms and Wyler 1979; Faulks 1981; Maga 1994) but they lack updates, are limited in scope in that they do not contain current information, and only a few papers deal with the influence of agronomic conditions on the volatiles (Khan et al. 1977; Hunnius et al. 1978; Fischer 1991; Jensen et al. 1999).

The volatiles in raw (Self et al. 1963b; Buttery and Ling 1973; Meigh et al. 1973; Khan et al. 1977; Fischer and Müller 1991) and boiled (Self et al. 1963b; Gumbmann and Burr 1964; Buttery et al. 1970; Buttery and Ling 1974; Josephson and Lindsay 1987), respectively, baked potatoes (Buttery et al. 1973; Pareles and Chang 1974; Coleman and Ho 1980; Ho and Coleman 1980) have been studied extensively.

Efforts have been made to differentiate which of these components are important for the characteristic flavour and which are specific to the type of cooking and preparation. Cultivar differences and influences due to agronomic and storage conditions have also been addressed (Duckham et al. 2001; Oruna-Concha et al. 2001; Duckham et al. 2002; Oruna-Concha et al. 2002a; Oruna-Concha et al. 2002b; Dobson et al. 2004).

But overall, the key contributors to potato flavour and taste have not been definitely identified (Morris et al. 2007), nor is it entirely clear which agronomic conditions influence the formation of volatile compounds.

4.2 Flavour nomenclature

The appreciation of flavour is a universal, everyday experience and is the integrated sensual response to a complex mixture of stimuli. Most predominant are the senses of smell and taste, but also decisive are sight (colour and appearance), tactile sensations (texture and mouth-feel) and pain (pungency) (Reineccius 1999; Kays and Wang 2000; Belitz et al. 2008).

The definition of flavour is the overall sensation resulting from the impact of the food on the chemical sense receptors in the nose and mouth. Taste is caused by stimulation of the gustatory cells of the buccal surface by soluble substances, nearly all of them non-volatile, released from the food into the saliva. Most of the flavour, however, is thought to be due to odorous volatile substances, released from the food into the air in the mouth and carried to the olfactory epithelium in the nose (Land 1979). When the odorous molecules pass from the mouth to the nose via the inner passages during the eating process, then the complex sensation of taste and odour is called flavour. But the most important characteristic of flavour is the odour (Reineccius 1999). This becomes obvious when a person catches a cold and can only sense flavour characteristics by the taste, tactile and temperature responses (Brillat-Savarin 1962; Land 1979; Heath and Reineccius 1986; Reineccius 1999).

It is important to note that a taste or odour is not an inherent property of a specific compound but is the psychological assessment of the individual sensing it. Therefore, the same compound can be perceived differently by different individuals or by the same individual at different times (Kays and Wang 2000).

4.3 Volatile Compounds

The presence and the level of volatile compounds generally determine the aroma and perceived flavour of a food (Maarse 1991; Whitfield 1992). Among the 7000 identified volatile compounds in foods, a relatively small number (300-400), in specific ratios, determine the characteristic odours of the product (Belitz et al. 2008). Analyses demonstrated that some very important aromas are not produced as a result of the presence of a unique characterizing compound; but rather a result of a reproducible blend of a particular number of components in proper balance. The compounds in potatoes predominantly include aldehydes, alcohols, ketones, acids, esters, hydrocarbons, amines, furans and sulphur compounds. The pattern and the number of volatile components obtained from potatoes can be quite different, depending whether raw potatoes are used or the method used to prepare them (Self et al. 1963; Johnson et al. 1971; Whitfield and Last 1991). Food produced with thermal process contains many more volatiles than the raw material (Belitz et al. 2008). These differences in amounts of volatiles depend on types of reactions, which increased with higher temperatures (see chapter 4.3.1.2).

Several factors make the analysis of flavours somewhat challenging, these include their presence at low concentrations (ppm, ppt), complexity of mixtures, extremely high volatility (high vapor pressures), and instability of some flavour compounds in dynamic equilibria with other constituents in foods (Lindsay 1996). The analysis of volatile compounds is generally conducted with gas chromatography (GC) combined with fast-scan mass spectrometry (MS) (Lindsay 1996; Reineccius 1999). As soon as the flavour of a food has been extracted, concentrated, separated and defined, a major question arises concerning each chemical´s meaning for the flavour. The instrument response for the flame ionization detector used in GC relates to the number of carbon-carbon bonds, whereas the human olfactory system varies greatly in response to different odours (Reineccius 1999). So it could be that the smallest peak in a GC can be more important to flavour formation than the largest peak. It must also be accepted that the GC provides no appreciation of the flavour character of each component (Reineccius 1999).

4.3.1 Volatile formation and its impact on flavour

The flavour of a raw or processed potato is very different, and it is quite difficult to specify the role of precursors in the various stages of the processes taking place in the raw and processed vegetable (Vernin 1982). The aroma of vegetables may be considered to originate from the basic nutrients such as carbohydrates, particularly the monosaccharide and disaccharide; proteins, and free amino acids; and fats, triglycerides or their derivates, as well as vitamins and minerals. These nutrients are produced by photosynthetic and related metabolic activities occurring in the plant (Salunkhe and Do 1976). In the following, the various groups of volatile aroma compounds are illustrated schematically (Figure 4.1), and the nutrients from which they derived are listed in the next table (Table 4.1).

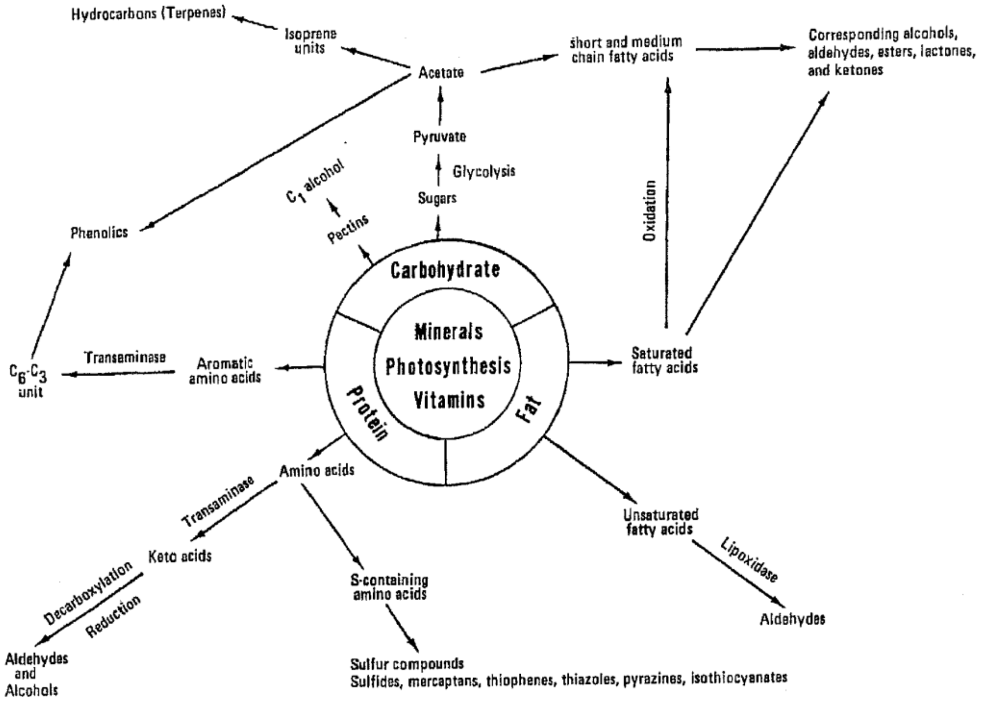

Figure 4.1: Formation of volatile aroma in fruits and vegetables.
From Salunkhe and Do (1976).

All vegetables have their own characteristic aroma, which is genetically controlled by the individual species (Heath and Reineccius 1986). But aroma is also influenced by cultivar, maturity, and horticultural practices (Reineccius 1999). However, only few studies exist on the biogenetic pathways of most of the aromatic components identified in raw potatoes.

Table 4.1: Predominant nutrients and their role in the production of aroma components in foods. According Salunkhe and Do (1976)

Nutrient	Aroma Component
Carbohydrates Glucose Fructose Sucrose	Organic acids: Pyruvic acid, acetic acid, propionic acid, acetoacetic acid, butyric acid, hexanoic acid, octanoic acid Esters: Pyruvates, acetates, propionates, butyrates, acetoacetates, hexanoates, octanoates Alcohols: Ethanol, propanol, butanol, hexanol, octanol Aldehydes: Acetaldehyde, propanal, butanal, hexanal, octanal Terpenes: Monoterpene, linalool, limonene, α-pinene, citronellal, citral, geranial
Amino acids	Pyruvic acid, acetaldehyde, ethanol
Alanine	Isopropanal, isopropanol, α-keto-isobutyric acid
Valine	3-Methylbutanal, 3-methylbutanol, α-keto-isocaproic acid
Leucine	2-Methylbutanal, 2-methylbutanol
Isoleucin Phenylalanine	Benzaldehyde, phenylacetaldehyde, cinnamaldehyde, Hydrocinnamaldehyde, ρ-hydroxybenzaldehyde, ρ-Hydroxy phenylacetaldehyde, ρ-hydroxy-cinnamaldehyde, ρ-hydroxy cinnamaldehyde
Serine	Pyruvic acid
Threonine	
Glycine	Thiazoles
Cystine/cysteine	Glyoxal
Serine	
Fatty acids	
Linoleic acid	*Trans*-2-*trans*-4-Decadienal, hexanal, *trans*-2-octanal
Linolenic acid	*Trans*-2-Pentanal, *trans*-2-hexenal, hexanal, cis-3-Hexenal, cis-3-hexenol, *trans*-2-*trans*-4-Heptadienal, propanal
Organic acids Citric acids Oxaloacetic acid Malic acid Lactic acid	Glyoxylic acid, glyoxal, pyruvic acid, acetaldehyde, Ethanol
Vitamins Carotenoids	
β-Carotene	β-Ionene
Thiamine	Thiazoles

Reasons for the limited amount of studies on the biogenetic pathways in the raw potato could be that mainly processed potatoes (boiled, baked, or in the form of French fries or chips) are consumed, and a lot of volatile compounds are formed during thermal processing. Thereby the temperature, blending speed and time, holding time, pH, and oxygen availability had a significant impact on the aroma profile (Salunkhe and Do

1976).

In the following, the different pathways of volatile formation and their impact on flavour are described.

4.3.1.1 Enzymatic Volatile Formation

Some volatile components may exist per se in the intact tissue of vegetables, but mainly physical damage and mechanical stress, including cellular disruption due to cutting a vegetable prior to use, to cooking, or to the chewing process permits the mixing of enzymes and non-volatile precursors which had been separated within the cell, resulting in the generation of volatile flavour substances (Heath and Reineccius 1986) which contribute significantly to the isolated aroma (Salunkhe and Do 1976). Furthermore, enzymes can be involved indirectly in flavour formation by procuring precursors, for example amino acids from proteins, saccharide from polysaccharide and o-quinone from phenolic compounds, which then react non-enzymatically to flavour compounds. In this way, enzymes are able to intensify the flavour (Tressl et al. 1975; Belitz et al. 2008). The non-volatiles are cysteine sulfoxides, thioglucosinolates and unsaturated fatty acids, which are transformed into volatile thio compound and carbonyls (Tressl et al. 1975; Reineccius 1999).

Lipids comprise a significant portion of horticultural crops and are primary components of the cell`s membrane system. Lipolytic acyl hydrolase liberates free fatty acids from phospholipids and glycolipids, the major lipids in potato (Galliard and Matthew 1973). Lipid content of the raw potato tuber is 0.2-0.3 g/100 g FM, of which the polyunsaturated fatty acids, linoleic and linolenic acids, account for 0.05 and 0.01 g, respectively (Galliard 1973).

Lipoxygenase (LOX) is one of the most widely studied enzymes in plants and animals. It catalyses the oxygenation of polyunsaturated fatty acids to form fatty acid hydroperoxides. The enzyme contributes to flavour formation, but it also has negative implications for the colour, off-flavour and antioxidant status of plant-based foods (Baysal and Demirdoven 2007).

The enzymatic influence on volatile flavour formation is only of little importance, because the potato is not consumed raw like other vegetables. Potatoes are consumed after processing and therefore, the thermal impact plays the most important role for the volatile flavour formation.

4.3.1.2 Volatile Formation by thermal impact

Precursors can also split by chemical reactions during the heating process. The volatile profile obtained from boiled and baked potatoes contains many process-derived compounds, which contribute to the overall potato flavour (Buttery et al. 1970; Maarse 1991). Important thermally driven reactions include the *Maillard* reaction, *Strecker* degradation and the thermal and enzymatic degradation of fatty acids (Figure 4.2) (Taylor et al. 2007).

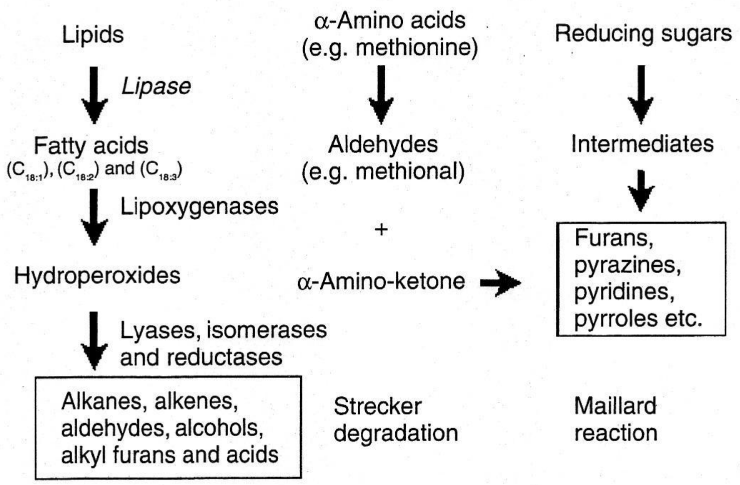

Figure 4.2: Origin of flavour volatiles released from boiled potatoes. Precursor metabolites are shown at the top, and the main products in boiling are shown in solid boxes. From Taylor et al. (2007)

The *Maillard* reaction, sugar degradation and lipid degradation (oxidative and thermal) are the most important reactions for the formation of volatile compounds in cooked and processed foods (Whitfield 1992).

4.3.1.2.1 *Maillard* reaction and *Strecker* degradation

The *Maillard* reaction (MR) and the *Strecker* degradation (SD) of α-amino acids are responsible for the formation of many heterocyclic compounds with distinctive aromas and low odour thresholds. The MR takes place when compounds possessing a carbonyl group, typically reducing sugars, react with components with a free amino group such as amino acids (Whitfield 1992; Taylor et al. 2007). The MR does not require high temperatures, however, the reaction rate increases markedly with temperatures associated with cooking. Furthermore, the reactions occur most frequently in areas of the product that have been dehydrated, such as near the surface (Kays and Wang 2000). The steps of the MR usually feature reactions with other intermediates, such as amino compounds or amino acid or lipid degradation products. Volatiles synthesized by the MR can be classified according to their primary precursor: 1) sugar degradation/fragmentation products, such as furans, pyrones (e.g., maltol), cyclopentenes, carbonyl compounds, and acids; 2) amino acid degradation products, such as aldehydes, sulfur compounds such as hydrogen sulfides and methanethiol, and nitrogen compounds such as ammonia and amines and 3) volatiles produced by further reactions, such as pyrroles, pyridines, pyrazines, imidazoles, oxazoles, compounds from aldol condensations, thiazoles, thiophenes, di- and trithiolanes, di- and trithianes, and furanthiols (Nursten 1980). Especially the pyrazines have a great diversity in odour within a class (Kays and Wang 2000).

The *Strecker* degradation (SD) of amino acids into their structurally related volatile counterparts is also very important in relation to the formation of a series of volatile flavour compounds (Whitfield 1992; Cremer et al. 2000; Rizzi 2008). The SD of amino acids has mainly been viewed as a corollary of the MR, and the primary reactants have been considered to be protein, i.e., amino acids and carbohydrates. According to Rizzi (2008), many of the numerous compounds that have been described in the literature as SD reaction products can be interpreted in terms of *Maillard* intermediates. However, in addition to carbohydrate reactants, it is also known that other important food ingredients like lipids and polyphenolic compounds can play a part in SD reactions to produce novel flavour compounds (Rizzi 2008). The SDs located in foods and during food processing are usually the reaction of α-amino acids with α-dicarbonyl compounds derived from concurrent *Maillard* reaction pathways. During the reaction, a α-amino acid undergoes decarboxylation and is transformed into a structurally related aldehyde (*Strecker* reaction) (Rizzi 2008). These corresponding “*Strecker* aldehydes” contain one less carbon atom than the original amino acids, and a α-amino ketone (Whitfield 1992). With cystein, in addition to the two normal products the reaction yields hydrogen sulphide, ammonia, acetaldehyde, and the regenerated dicarbonyl compound. The amino ketones can act as reducing agents, and it has been proposed that hydrogen sulphide is also formed by the reduction of cysteine itself or 2-mercaptoacetaldehyde (Whitfield 1992). The *Strecker* degradation of methionine is another source of sulphur-containing intermediates. In this case, the reaction involves the interaction of α-dicarbonyl compounds, intermediates the *Maillard* reaction, with methionine, resulting in the formation of 2-methylthiopropanal, also called as methional (Lindsay 1996) and methanethiol with 2-propenal as the co-product (Fujimaki et al. 1969). Methional is deemed to be the key compound of boiled potato flavour (Petersen et al. 1998).

The interaction of the *Maillard* reaction products with those of the *Strecker* degradation led to the formation of many important classes of flavour compounds. These include pyrazines, oxazoles, thiophenes, and other heterocyclic compounds with more than one sulphur atom. But also lipid and lipid degradation products can be involved in these reactions, leading to the formation of additional compounds and the reduction or prevention of the formation of the normal products of a *Maillard* reaction (Whitfield 1992).

4.3.2 Raw Potatoes

Although potato tubers are only consumed after cooking, there is an interest to identifying the volatiles in the raw product (Taylor et al. 2007). This provides a reference point when evaluating the formation of flavour compounds during the processing of various potato products. The state of knowledge about the spectrum of volatile compounds in raw potatoes, which is characterized by a weak but typical odour, is very limited (Fischer and Müller 1991). About 159 volatiles have been identified in raw potatoes, independent of the analytical method, varieties, and whether peeled or unpeeled. These are summarized in Table 4.2 at the end of Chapter 4.3.2.

Most of studies have concentrated on cut or sliced potatoes, which cause an oxidative and enzymatic attack on inherent lipids. This obviously results in a vast amount of unsaturated and saturated aldehydes and alcohols, several of which have extremely low odour thresholds and therefore probably a negative impact on flavour (Petersen et al. 1998). Analyses by Schormüller and Weder (1966b), as well as by Khan et al. (1977), detected primarily short-chain alcohols, aldehyde, ketone, thiazoles and sulphur compounds are discovered in raw potatoes. Buttery and Ling (1973) hypothesized that raw potato volatiles are derived from biosynthetic processes in the tuber or associated microorganisms rather than from thermally catalysed reactions. Lipid oxidation products of unsaturated fatty acids are the major source of volatiles in raw potatoes, because the lipoxygenase content is relatively high (Josephson and Lindsay 1987; Fischer and Müller 1991; Petersen et al. 1998). These dominated the constituent’s 2-octenal, hexanal, heptanal, pentanol, 2-pentylfuran as well as 2-methyl- and 3-methylbutanol. The high amount of 2-methyl- and 3-methylbutanol is a sign of intensive amino acids metabolism in the tuber, because both compounds arise from the enzymatic degradation of leucine rather isoleucine (Drawert 1975). When slicing or shredding potato tubers, there is a large increase in hexanal, octenal and isomeric forms of 2,4-decadienal, all products of lipoxygenase-initiated reactions of unsaturated fatty acids, taking place soon after the disruption of cells (Josephson and Lindsay 1987; Petersen et al. 1998). The following volatiles, which were also found in raw potatoes, belonging to the products of lipoxygenase-initiated reactions: heptanal, 1-penten-3-one, 1-pentanol, 2,4-heptadienal, 2,6-nonadienal and 2-pentyl furan (Schieberle and Grosch 1981; Josephson and Lindsay 1987; Ho and Chen 1994; Sok and Kim 1994; Gardner et al. 1996; Petersen et al. 1998). This could explain the observation of Self et al. (1963b; Petersen et al. 1998), who noted that the aroma of fresh-cut potatoes was different from that of whole potatoes, but made no attempt to identify responsible compounds. Buttery and Ling (1973) as well as Murray and Whitfield (1975) found compounds such as methoxypyrazines in raw potatoes. They assumed that they were derived from biosynthetic processes. Morgan et al. (1972) reported that 2-methoxy-3-isopropylpyrazine occurs in relatively large concentrations in the cultures of the microorganism *Pseudomonas taetrolens*. They guessed that the small concentration that occurs in potatoes might first be formed in the soil or on tuber surface (by this or some related microorganism) and then be absorbed into the potato. However, the potato plant is botanically related to the bell pepper plant, which produces relatively large amounts of 2-isobutyl-3-methoxypyrazine and probably is quite capable of producing the compound itself. The occurrence of relatively high amounts of methoxypyrazines in peeled tubers may argue against the synthesization of this compound by soil microflora associated with the tuber, and indicate that a biosynthetic route for their production is present in the potato tuber. The most identified methoxypyrazine present in raw potato volatiles was 2-methoxy-3-isopropylpyrazine (Murray and Whitfield 1975). Methoxypyrazines have very low odour thresholds and have characteristic vegetable-like odours, including potato-like odours. In contrast to this analysis by Murray and Whitfield (1975), Fischer and Müller (1991) did not find any pyrazines in the analysis of raw potatoes.

Desjardins et al. (1995) were the only researchers to also find the hydrocarbon sesquiterpenes in raw potatoes and detected them at higher levels after tuber damage or microbial attack. It could be demonstrated that fungal and bacterial infections (*Erwinia carotovora* ssp. *atroseptica*, *Phytopthora infestans*) lead to an increase of the potato stress metabolite solavetivone, a sesquiterpene (Zacharius and Kalan 1984). This observation by Desjardins et al. (1995) showed that the raw potatoes tested were stressed or infected.

Individually, raw potatoes include many potent flavours, which represent juicy, earthy, oily as well as nutty- and roast-like flavour notes. For the description of the typical raw potato flavour, no single component would even suggest the familiar aroma.

Table 4.2: Volatiles identified in raw, boiled and baked potatoes with their odour description specified in the literature

Compound	**Raw***	**Boiled***	**Baked***	**Odour description all**
Aldehydes				
Acetaldehyde	1-9, 24, 25	1, 3, 14, 16, 26, 27		
Isobutyraldehyde		1, 3, 14, 18, 26, 27		
Propanal	1, 2, 5-9, 24, 25	1, 6, 16, 26, 27		
Acrolein (= Propenal)		1, 3, 16, 27		
2-Propenal	1, 3, 6, 7, 9			
Methylpropanal		33, 36		malty
2-Methylpropanal	1, 3, 5-10		7, 37, 38, 44	
2-Methyl-2-propanal			38	
Butanal	3, 6, 9, 24, 25	3		
2-Butenal	6, 9	31		
2-Methylbutanal	1, 6, 7, 10	16, 33, 36	7, 37, 43-45	sweet, chocolate, sometimes roasted/toasted, malty
3-Methylbutanal	1, 3, 5-9	1, 3, 16, 26, 27, 33, 36	7, 37, 43-45	sweet, chocolate, sometimes roasted/toasted, malty
3-Methyl-1-butenal			38	
2-Methyl-2-butenal			38, 47	
3-Methyl-2-butenal			38	
Pentanal	2, 5, 6, 8, 9, 23		38, 43-45, 47	green, almond, marzipan
Pentenal	29, 30, 40	31, 34, 35	47	roasty, rubber, unpleasant
2-Pentenal	6, 7	35	38, 45, 47	
4-Methyl-2-phenyl-2-pentenal			38	
Hexanal	2, 5-9, 11-14, 23	6, 14, 28, 31-36	7, 37, 38, 43-47	green, grass, fatty
2-Ethylhexanal			38	
5-Methyl-2-phenylhexanal			38	
2-Hexenal	2, 5-14	6, 12, 34, 35	7, 37, 47	
3-Hexenal			37, 38	green, bitter-almond-like
Heptanal	2, 6, 7, 9, 11, 13-15, 23	6, 12, 14, 23, 34	7, 37, 38, 43-47	soapy-fruity, resinous
Heptenal			7, 37	
2-Heptenal	23	6, 14, 23, 31, 34, 35	45-47	cardboard-like
4-Heptenal		12, 23		earthy, prepared food, potato-like
Octanal	2, 9, 11, 13	12, 31, 34-36	43, 45, 47	fatty, soapy-fruity, citrus-like
Octenal		6, 12	7, 37	

[*] References 1-47 are listed at the end of the table

Table 4.2 (continued)

2-Octenal	2, 6, 7, 9, 12-14, 23	23, 34-36	45, 47	fatty, nutty, baked potato, chips
2,4-Octadienal		31		
Nonanal		6, 12, 34, 35	7, 37, 38, 43-47	rancid, boiled potato
2-Nonenal	6, 7, 9, 13, 14, 23	6, 12, 14, 32-34, 36	7, 37, 43, 45, 47	sweet, green, cucumber
3-Nonenal		36		green, tallowy
Decanal	6	6, 12, 18, 32, 34	7, 37, 43-46	
Undecanal			38, 43, 45, 46	metallic
2-Undecanal			46	
Dodecanal			43, 45	
2-Dodecanal			46	
Hexadecanal			46	
Octadecanal			38	
Decenal			7, 37	
2-Decenal		36		fatty
2,4-Decadienal	6, 7, 12-15, 23	6, 12, 14, 30, 32-36	7, 37, 46	fatty, green, onions, chips, chip fat, hot potato, liquorice, roasty
2,4-Heptadienal	6, 13, 23	6, 12, 34, 35	7, 37, 46, 47	oily, rancid nuts, mushroom
Nonadienal			7, 37	
2,4-Nonadienal	13, 23	12, 32, 34-36	46, 47	fatty-soapy/-oily, old, rancid, nutty, almond, marzipan
2,6-Nonadienal	23	12, 23, 30, 32, 35, 36		fatty, green, cucumber, grass, peas, paint, vinegar-dressed
Benzaldehyde	6, 7, 14	6, 12, 14, 35	7, 37-39, 43-47	flowery
Phenylacetaldehyde	6, 7, 14, 23	30, 36	37-39, 43-47	earthy, flower, roses, sweet, honey-like
Ethylbenzaldehyde			38	
2,5-Dimethylbenzaldehyde			38	
Methoxycinnanaldehyde			38	
Salicaldehyde			38	
Methional (=3-(Methylthio)propanal)	6, 7, 14	5, 14, 23, 28, 30, 32-36	43, 44, 46, 47	boiled potato
trans-4,5-Epoxy-(E)-2-decenal		32, 33, 36		metallic
trans-4,5-Epoxy-(E)-2-nonenal		36		metallic
Furfural	6, 7, 14	12, 14	47	
2-Furfural			43-46	
5-Methylfurfural			46	
5-Methyl-2-furfural			46	
5-Methyl-2-thiophenecarbox-aldehyde			46	
Vanillin		32, 33, 36		sweet, vanilla-like

Table 4.2 (continued)

Alcohols				
Methanol	1, 6, 7, 16, 21, 24, 25	16, 26, 27	38	
Ethanol	1, 6, 7, 21, 23-25	27	38	
2-Methyl-1-propanol	6, 24, 25			
1-Butanol	6, 21, 24, 25	28		
2-Butanol	24, 25		38	
2-Buten-1-ol	6	6		
Propanol	11, 24, 25			
2-Propanol	24			
1-Butoxy-2-propanol		35		
2-Methylbutanol	3, 6, 7, 13, 14, 21, 23	14, 30	43, 44, 47	malty
3-Methybutanol	3, 6, 7, 13, 14, 21	6, 14	43, 44, 46, 47	malty
Pentanol	6, 7, 13-15, 21, 23	6, 12, 14, 28, 34, 35		malty
2-Pentanol			38	
2-Methyl-2-pentanol			38	
3-Methyl-1-pentanol		35	38	
4-Methyl-1-pentanol	21			
2,4-Dimethyl-3-pentanol			38	
4-Methyl-4-pentenol			38	
2-Methyl-3-penten-2-ol			38	
2-Methyl-1-penten-3-ol			38	
Hexanol	6, 13, 21	6, 12, 34, 35	43, 47	green, flowery
2-Ethyl-1-hexanol			47	
Hexenol	6			
2-Hexen-1-ol	6	28		
3-Hexen-1-ol			47	
3-Methyl-2-hexanol	6	6		
Nananol		35		
Heptanol	17, 21	6	38	
2-Heptanol		23		popcorn
Octanol	17	6, 30, 31		
3,6-Dimethyl-3-octanol			38	
2-Isobutyloctanol			38	
Octenol	6, 7, 14			
2-Octen-1-ol		12, 14		
1-Octen-3-ol	6, 7, 13, 14, 17	6, 12, 14, 34, 35	37, 38, 43-47	fungus, mushroom
Non-3-enol	17			
Geraniol	6, 7, 14			
Nerol	6, 7, 14	6, 14		
Nerolidol		31		
Linalool	6, 7, 14	14, 34	43, 47	
Benzyl alcohol	6, 7, 14, 23	14, 28, 35	38	Flower, citrus, fruit

Table 4.2 (continued)

2-Phenylethanol	6	28, 35		
Terpineol	6, 7, 14	14		
Terpenol		37		
Furfuryl alcohol		31		
cis-Farnesol		31		
Menthadienol		31		unpleasant, sweet
1,2-Ethanediol		35		
2-(2-Butoxyethoxy)-ethanol		35		
Dodecanol			38	
Hexadecanol			38, 46	
Cyclohexanol			38	
2-Tetradecyloxyethanol			38	
Hexahydrofarnesol			38	
Trimethylbenzyl alcohol			38	
3-Methoxy-4-isopropylbenzyl alcohol			38	
Naphthol			38	
2-Methoxyphenol			46	
Eugenol			46	
4-Vinyl-2-methoxyphenol			46	
2-Methoxy-4-vinylphenol			46	
Ketones				
Acetone	1, 3, 6, 7, 9, 24	1, 3, 16, 26, 27	38	
3-Methyl-2-butanone	3, 6, 9	3		
3-Hydroxybutanone	24			
3-Hydroxy-2-butanone	25			
Butanedione			43, 44	
2,3-Butanedione (= Diacethyl)	6, 11	31, 36		buttery
2,3-Pentanedione	6	12	43, 44, 47	
Propanone	11			
2-Propanone	25			
1-Phenyl-1,2-propanedione			38	
Butanone	11		43	
2-Butanone	24, 25	31	45	
3-Pentanone			43	
4-Methyl-2-pentanone			38	
5-Methoxy-2-pentanone			38	
3-Ethylcyclopentanone			46	
Cyclopentanone			38	
2,5-Dimethyl-1-cyclopentanone			38	
2-Pentadecanone			46	
4-Methyl-3-penten-2-one			38	
2,6-Dimethyl-3-penten-2-one			38	
Hexanone	11		38	
3-Hexanone			43	
2-Acetyl-3,3-dimethylcyclohexanone			38	

Table 4.2 (continued)

3,5, 5-Trimethyl-3-cyclohexene-1-one			45, 46	
Heptanone	2, 6, 7, 11, 14		7, 38	
2-Heptanone		6, 14	37, 38, 44, 47	
4-Heptanone			7, 37, 38	
2-Methyl-4-heptanone			38	
2-Methyl-2-hepten-6-one			38	
6-Methyl-5-hepten-2-one			43, 45, 47	
Octanone	2, 11			
1-Octen-3-one	6, 7, 14	12, 14, 32, 36		mushroom-like
3-Octen-2-one			38	
4-Octen-3-one			47	
1-Penten-3-one	23	31		
Nonanone	2, 11			
2-Nonen-4-one	6, 7, 14	14, 31		
2-Decanone	6, 7, 14	14		
4-Decanone			38	
2-Undecanone		12		
2,3-Octanedione			46, 47	
3,5-Octadien-2-one		12, 30, 31	46	
1,5-Octadien-3-one		12, 32, 36		geranium-like
2-Methyl-3-octanone		31		
1-Methyl-2-pyrrolidinone	23			
Furyl methyl ketone		28		
1-Furyl-2-propanone		28		
1,2-Cyclohexanedione		31		
Farnesyl acetone		31		
Geranylacetone		31	43	
(E)-β-Damascenone		32, 36	43	fruity, sweet
Decalactone		32, 36		sweet, peach-like
Octalactone		36		sweet, coconut-like
Nonalactone		36		sweet, coconut-like
Acetophenone			45	
ρ-Methyl acetophene			38	
Solavetivone			46	
Isophorone			43	
Camphor			45	
Acids				
Acetic acid	7, 23	23, 28, 35	38	
Propanoic acid	23		38	
Butanoic acid		36	38	
Decanoic acid	5, 8			
Tetradecanoic acid	5, 8			
Pentanoic acid		36	38	

Table 4.2 (continued)

Pentadecanoic acid	5, 8			
Hexanoic acid	23	12, 35	38	prepared food, soup, cake, raw potato
Hexadecanoic acid	5, 8			
9-Hexadecanoic acid	5, 8			
Heptanoic acid			38	
Heptadecanoic acid	5, 8			
Octanoic acid		35, 36		
Octadecanoic acid	5, 8			
cis-9-Octadecanoic acid	5, 8			
9,12-Octadecanoic acid	5, 8			
9,12,15-Octadecatrienoic acid	5, 8			
Eicosanoic acid	5, 8			
Phenylacetic acid	7	28		
2-Methylhexanoic acid			38	
2-Methylpentanoic acid			38	
2-Methylpropanoic acid			38	
2-Phenylcrotonic acid			39	
3-Methylbutanoic acid			36, 38	
3-Methylpentanoic acid			38	
4-Methylpentanoic acid			38	
2-Ketoadipic acid			38	
Esters				
1-Methylpropyl acetate			38	
2-Methylbutyl acetate			38	
2-Methylbutyl pentanoate			38	
Allyl hexanoate			38	
Butyl acetate			38, 45	
Butyl byturate		34		
Diethyl phthalate			38	
Di-isobutyl isophthalate			38	
Di-isobutyl phthalate			38	
Ethyl acetate			38, 43	
Ethyl benzaldehyde		12		
Ethyl heptanoate		12		
Hept-1-enyl 2 acetate			38	
Methyl 2-hydroxybenzoate	6, 7, 14			
Methyl 2-methylbutanoate			38, 45, 47	
Methyl 2-methylpentanoate			38	
Methyl 2-methylpropanoate			43	
Methyl hexadecanoate			46	
Methyl hexanoate			38	
Methyl nonanoate			38	
Methyl octadecanoate			46	
Methyl octanoate			38	
Methyl pentanoate			38	

Table 4.2 (continued)

Methyl salicylate		14		
Methyl tetradecanoate			46	
Methylbutanoate			43, 45, 47	
Octadecyl acetate			46	
Pentyl acetate			38	
Phthalic anhydride			38	
Lactones				
4-Pyridoxic acid lactone			38	
Hydrocarbons				
Octane		18	45	
Hexane			45	
Nonane			45	
Decane	6	18	45	
Tridecane			45	
Tetradecane	6	31	45	
2-Methyldecane			45	
4-Methyldecane			45	
2-Methyltetradecane			38	
Pentadecane		31	45	
2,6,10,14-Tetramethylpentadecane			38	
Hexadecane			45	
5,7-Dimethylhexadecane			38	
7,9-Dimethylhexadecane			38	
2,6,11,15-Tetramethylhexadecane			38	
Heptane		18	45	
Cycloheptane			46	
2,4-Dimethylheptane			38	
9-Octylheptadecane			38	
2,2,4,6,6-Pentamethylheptane			45, 47	
Cyclodecane			38	
Undecane	6		45, 46	
2,6,9-Trimethylundecane			38	
2,6,10-Trimethylundecane			38	
Dodecane	6		45	
1-Dodecane			45	
4,6-di-*n*-Propyldodecane			38	
1-Cyclopentyl-4-octyldodecane			38	
(E)-9-Octadecene	23			
Copaene			43-45, 47	
1,1-Diethoxyethane			39	
3,5,5-Trimethyl-1-hexene			38	
2-Ethyl-3-octene			38	
4-Ethyl-3-octene			38	
1-Octadiene			38	
1,4-Dimethyl-4-vinylcyclohexene			38	

Table 4.2 (continued)

1,1-Dichloroheptane			38, 42	
1-Chlorohexadecane			38, 42	
o-Chloroaniline			38, 42	
p-Chloroaniline			38, 42	
2-Chlorobiphenyl			38, 42	
Trichloroacetic acid			38, 42	
20-Bromo-5-ethylnonane			38, 42	
1-Iodo-octadecane			38, 42	
Diphenylmethane			38	
1-Methylindan			38	
4,5,7-Trimethylindan			38	
α-Aromadendrene			43, 45	
Guaiene			43	
Cyclosativene			45	
Longicyclene			45	
Gurjunene			45	
Limonene	6	6	38, 43-47	
α-Pinene	6	6	38, 43-45, 47	
β-Pinene	6	6		
3-Carene	6	6	38, 43-45, 47	
Benzene	6	18	38, 43, 47	
Methylbenzene (=Toluene)	6	18	38, 43, 45, 47	
Ethylbenzene	6	6	43, 45-47	
Dimethylbenzene (= Xylene)		6, 18		
1,2-Dimethylbenzene	6		38, 43, 45, 47	
1,3-Dimethylbenzene	6		38, 43, 45, 47	
1,4-Dimethylbenzene	6		38, 43, 45, 47	
Isopropylbenzene			38	
1-Ethyl-2-methylbenzene	6	6		
1-Ethyl-4-methylbenzene	6	6		
2-Ethyl-6-propylpyrazine			38, 40	
2-Ethyl-3,5,6-trimethylpyrazine			38, 40	
Trimethylbenzene			38, 47	
1,2,3-Trimethylbenzene	6	6		
1,2,4-Trimethylbenzene	6			
1,3,5-Trimethylbenzene	6	6		
2,3,6-Trimethyl-5-hydroxy-cyclopentapyrazine			38, 40	
Pentylbenzene			45	
Propylbenzene			45-47	
Alkylbenzene			45	

Table 4.2 (continued)

Vinylbenzene (=Styrene)			43	
2-Methylvinylbenzene			47	
3-Ethylstyrene			38	
tert-Butylbenzene			38	
sec-Butylbenzene			38	
1,2,3,5-Tetramethylbenzene			38	
Hexamethylbenzene			38	
1-Methyl-4-ethylbenzene			38	
Methylpropylbenzene			45, 47	
Ethyldimethylbenzene			45	
Nonylbenzene			38	
Biphenyl	6, 7, 14	14	38	
Diphenylmethane			38	
Naphthalene	6, 7, 14	14, 18	43, 45, 47	earthy
2,6-Naphthalene	18			
1-Methylnaphthalene	18	14, 18		
2-Methylnaphthalene	6, 14		46	
Dimethylnaphthalene	6	6		
1,2-Dimethylnaphthalene			38	earthy
1,3-Dimethylnaphthalene			38	earthy
1,4-Dimethylnaphthalene	18			
1,6-Dimethylnaphthalene	18			
2,7-Dimethylnaphthalene			38	earthy
2,5-Diethyl-3-methylpyrazine			7, 37	
2,6-Diethyl-3-methylpyrazine			37	
Trimethylnaphthalene	18			
1,3,8-Trimethylnaphthalene			38	earthy
1,4,5-Trimethylnaphthalene			38	earthy
1,4,6-Trimethyl-1,2,3,4-tetrahydronaphthalene			38	
Decahydronaphthalene			45	
2-Isopropylnaphthalene			38	earthy
3-Methyleicosane			38	
Methylcyclopentane			38, 43	
Sesquiterpene	22			
γ-Hunulene			38	
Myrcene			38, 43, 47	
Ocimene			43	
Cymene		34	38, 44, 47	
Curcumene			45	
Terpinolene			44	
trans, *trans*-Farnesene			38	
Phellandrene			38, 44	
Pyrazines				
2,3,5-Trimethyl-6-(3-methylbutyl)pyrazine			46	
2,3,5-Trimethylpyrazine			37, 38, 40	

Table 4.2 (continued)

2,3,6-Trimethyl-5-hydroxy-cyclopentapyrazine			38, 40	
2,3-Diethyl-5-methylpyrazine	19	32, 33, 36	7, 37-40, 43, 46	earthy, roasty
2,3-Diethylpyrazine			38, 40	
2,3-Dimethyl-5-butypyrazine			38, 40	
2,3-Dimethylpyrazine			7, 37, 38, 40	
2,5-Diethyl-3-methylpyrazine			7, 37	
2,5-Dimethyl-3-(2-methylpropyl)pyrazine			46	
2,5-Dimethyl-3-(3-methylbutyl)pyrazine			46	
2,5-Dimethyl-3-butylpyrazine			38, 40	
2,5-Dimethyl-3-propenylpyrazine			46	
2,5-Dimethylpyrazine			7, 37-40, 43, 44, 46, 47	
2,6-Diethyl-3-methylpyrazine			37	
2,6-Dimethyl-3-(2-methylbutyl)pyrazine			46	
2,6-Dimethyl-3-butylpyrazine			38, 40	
2,6-Dimethylpyrazine		30	7, 37-40, 43, 44, 46, 47	nutty, warm
2-Butyl-3-methoxypyrazine	19			potato-like odour
2-Butyl-3-methylpyrazine			38, 40	
2-Butyl-6-methylpyrazine			38, 40	
2-Ethenyl-5-methylpyrazine			46	
2-Ethenyl-6-methylpyrazine			46	
2-Ethoxy-3-ethylpyrazine		6		not distinctive
2-Ethoxy-3-methyl-pyrazine		6		not distinctive
2-Ethyl-3,5,6-trimethylpyrazine			38, 40	
2-Ethyl-3,5-dimethylpyrazine			38, 40	roasty, coffee-like
2-Ethyl-3,6-dimethylpyrazine			37-40, 43, 46	earthy, buttery, baked, potato-like
2-Ethyl-3-methoxypyrazine		6		
2-Ethyl-3-methylpyrazine			7, 37-40, 43, 46	earthy, nutty
2-Ethyl-5-methylpyrazine			7, 37-40, 43, 46	
2-Ethyl-6-methylpyrazine		30	7, 37-40, 43, 46	nutty, warm, chemical
2-Ethyl-6-propylpyrazine			38, 40	
2-Ethyl-6-vinylpyrazine			38, 40	buttery, baked, potato-like
2-Isobutyl-2,5-dimethylpyrazine			40	
2-Isobutyl-3,6-dimethylpyrazine			39	
2-Isobutyl-3-methoxypyrazine	19	23, 33, 36	43-45	potato-like, pepper-like, green
2-Isobutyl-3-methylpyrazine			7, 37-40	

Table 4.2 (continued)

2-Isobutyl-5-methylpyrazine			39	
2-Isopropyl-3-methoxypyrazine	6, 7, 14, 17, 19, 20	6, 17, 32, 36	40, 43, 44, 46, 47	earthy/green, pea-like
2-Methoxy-3,5-dimethylpyrazine		6		bready
2-Methoxy-3-ethylpyrazine		6		raw potato
2-Methoxy-3-isopropylpyrazine		12, 17, 18		earthy, green, peas, raw potato, dry
2-Methoxy-3-methylpyrazine		6		nutty
2-Methoxy-5,6-dimethylpyrazine		6		Caraway seed
2-Methoxy-5-ethylpyrazine		6		bready/mousy
2-Methoxy-5-methylpyrazine		6		not distinctive
2-Methoxy-6-ethylpyrazine		6		bready/mousy
2-Methoxy-6-methylpyrazine		6		Fruit squash note
2-Methyl-3-isopropylpyrazine	6	12, 17, 18		nutty, warm, chemical
2-Methyl-5-isopropylpyrazine		30		
2-Methyl-5-propenylpyrazine			46	
2-Methyl-5-vinylpyrazine			7, 37	
2-Methyl-6,7-dihydro-5*H*-cyclopentapyrazine			38, 40	earthy, baked-potato-like
3,5-Diethyl-2-methylpyrazine			7, 37-40, 43, 46	
3,5-Dimethyl-2-(2-methylpropyl)pyrazine			44, 46	
3,5-Dimethyl-6,7-dihydro-5*H*-cyclopentapyrazine			38, 40	earthy, baked-potato-like
3-Butyl-2,5-dimethylpyrazine			38, 40	
3-Ethyl-2,5-dimethylpyrazine		30	37, 38, 40, 43, 46	nutty, earthy, herbaceous
3-Ethyl-2-methoxypyrazine		6		earthy/green
3-Ethyl-2,5-dimethylpyrazine			47	
3-Isoamyl-2,5-dimethylpyrazine			40	
3-Isobutyl-2,5-dimethylpyrazine			7, 37, 39, 40	
3-Isopropyl-2-methoxypyrazine		23, 29, 32	43	earthy, green, peas, raw potato, dry
5,7-Dimethyl-1,2,3,4,7,8-hexahydroquinoxaline			38, 40	earthy, baked-potato-like
5-Butyl-2,3-dimethylpyrazine			38, 40	
5-Methyl-6,7-dihydro-5*H*-cyclopentapyrazine			38, 40	earthy, baked-potato-like
Amylmethylpyrazine			37	
Diethylpropylpyrazine			37	
Dimethylpropylpyrazine			37	
Ethyldimethylvinylpyrazine			37	
Ethylpyrazine			7, 37, 38, 40, 43, 46	
Ethylvinylpyrazine			37	
Isoamyldimethylpyrazine			37	

Table 4.2 (continued)

Isoamypyrazine			37	
Isobutyldimethylpyrazine			37	
Isobutylethylmethylpyrazine			37	
Methylpyrazine		30	7, 37, 38, 40, 43, 44, 46, 47	nutty, strong
Trimethylpyrazine			46	
Pyridines				
Pyridine	6, 7, 14	14, 18	7, 37, 43, 44, 46	
2-Pyridine methanol		31		
2-Aminopyridine			38	
2-Acetylpyridine			38	
Pyrroles				
2-Acetylpyrrole			38, 41, 46	
2-Acetyl-1-pyrroline		32, 36	38, 41, 46	roasty, popcorn
N-Methyl-2-formylpyrrole			38, 41	
1-Methyl-1(*H)*-pyrrole			43, 45, 46	
1-(2-furanylmethyl)-(1*H*)-pyrrole			46	
Furans				
Furan	6			
2-Furaldehyde			38, 39, 41	
2-Ethylfuran	6, 23	31, 34, 35	43-45, 47	sweet, burnt
2-Pentylfuran	6, 7, 13, 14, 23	6, 12, 14, 23, 30, 34, 35	7, 37, 38, 41, 43-47	unpleasant, green, beany, grassy, cooked
2-Acetylfuran	6		7, 37, 38, 41	
2-Methylfuran		18	43-45	
3-Methylfuran		18		
2-Butylfuran		18		
2-Hexylfuran		18		
2-Propionylfuran			38, 41	
1-(2-Furyl)-2-propanone	6			
5-Methylfurfural		31	7, 38, 39, 41	
4-Hydroxy-2,5-dimethyl-3(2H)-furanone		32, 33, 36		caramel-like
3-Hydroxy-4,5-dimethyl-2(5H)-furanone		32, 33, 36		spicy, seasoning-like
trans-2-(2-Pentenyl)furan			38, 41	
Methyl furoate			38, 41	
2,5-Dimethyltetrahydrofuran			38, 41	
2-Methyltetrahydrofuran-3-one			38, 41	
2-Methyl-3-(2*H*)-furanone			38, 41, 47	
2,5-Dihydrofuran			46	

Table 4.2 (continued)

Amines				
Methylamine	21			
Propylamine	21			
Isobutylamine	21			
Diethylamine	21			
Ethers				
Methyl ether			38	
Diethyl ether	6			
Ethyl isopropyl ether			38	
Ethyl pentyl ether			38	
Methyl nonyl ether			38	
Diethylene glycol diethyl ether			38	
1-Ethoxy-1-propoxyethane			38	
1,1-Diethoxyisopentane			38	
Halogens				
Bromodichloromethane	6			
20-Bromo-5-ethylnonane			38, 42	
Chloroform			38, 42	
1,1,1-Trichloroethane			38, 42	
Tetrachloroethylene			38, 42	
2-Chloropropane			38, 42	
1-Chloro-2-methylbutane			38, 42	
1-Chloroheptane			38, 42	
2-Chlorobiphenyl			38, 42	
1-Chlorohexadecane			38, 42	
1,1-Dichloroheptane			38, 42	
o-Chloroaniline			38, 42	
p-Chloroaniline			38, 42	
1-Iodo-octadecane			38, 42	
Thiazoles				
Dipropylthiazole	20	20		
2,4,5-Trimethylthaizole	20	20		
Ethyl-dimethylthaizole	20	20		
2-Isopropyl-4,5-dimethylthiazole	20	20		
2-Isobutyl-4,5-dimethylthiazole	20	20		
2-Isopropyl-4-methyl-5-ethylthiazole	20	20		
Benzothiazole	6, 10, 14	14		
2-Acetylthiazole	20	20		
2,5-Dimethyl-4-ethylthiazole			38, 40	earthy, nutty
2,5-Dimethyl-4-butylthiazole			38, 40	earthy, nutty
2,5-Diethyl-4-methylthiazole			38, 40	sweet, earthy
Thiophenes				
Thiophene			38, 41	
Benzothiophene		18		

Table 4.2 (continued)

2-Formylthiophene			38, 41	
2-Butyl-6-ethylthiophene			38, 41	
Oxazoles				
2,4,5-Trimethyloxazole			38, 41	earthy, nutty
5-Acetyl-2,4-dimethyloxazole			38, 41	earthy, nutty
Sulphur compounds				
Methanethiol	1, 3, 5-7,16	1, 3, 5, 16, 26, 27, 32, 33, 36		cabbage-like, sulfury
Ethanethiol	1, 3, 5-7,16	1, 3, 5, 16, 26, 27		
Butanethiol		5		
1-Propanethiol	1, 5-7	1, 5		
2-Propanethiol	1, 5-7	5		
2-Methyl-2-propanethiol	1, 5, 6			
Hydrogen sulphide	1, 3, 6, 7,16	1, 3, 5, 16		
Methylpropyl sulphide	1, 5, 6	5		
Methylpropyl disulphide			46	
Methyl *N*-pentyl disulphide			46, 47	
Ethylmethyl sulphide	1, 5-7	5		
Ethylmethyl disulphide	1, 5-7	5		
Dimethyl sulphide	1, 3, 5, 16	1, 3, 5, 16, 26, 27, 32, 33, 36	45	sulfury
Dimethyl disulphide	1, 5-7		43-47	
Dimethyl trisulphide		31-33, 36	43-47	cabbage-like
Dimethyl tetrasulphide		31	43-47	cabbage-like
3,5-Dimethyl-1,2,4-trithiolane	6, 7, 14	14		
Dimethyl sulphoxide		34		
Diethyl sulphide	1, 5-7	5		
Isopropylmethyl disulphide	1, 5-7	5		
2-Ethylhexyl mercaptan			38	
Ethyl pentyl disulphide			46	
2-Isopropylbenzimidazole			38	
Benzyl methyl sulphide			46	
Benzyl methyl disulphide			46	
Dipentyl disulphide			46	
Nitrogen compounds				
Diethylformamide			38	
Diethylacetamide			38	
Diphenylamine			38	
Thymine			38	
Cyanobenzene			38	
2-Amino-4-nitrotoluene			38	
2-Aminopentane			38	

Table 4.2 (continued)

Miscellaneous compounds				
Benzaldehyde diethylacetal	6	28		
Pentyl oxirane		12		
2-Propyl-1,3-dioxolane			38	
2,4,6-Trimethyl-1,3,5-trioxane			38	

1= Self (1967); 2= Khan et al. (1977); 3= Self et al. (1963b); 4= Dumelin and Solms (1976); 5= Gumbmann and Burr (1964); 6= Nursten and Sheen (1974); 7= Sapers (1975); 8= Buttery et al. (1961); 9= Schormüller and Weder (1966b); 10= Buttery and Teranishi (1963); 11= Khan (1971); 12= Josephson and Lindsay (1987); 13= Fischer and Müller (1991); 14= Buttery et al. (1970); 15= Fischer (1991); 16= Self et al. (1963a); 17= Buttery and Ling (1973); 18= Meigh et al. (1973); 19= Murray and Whitfield (1975); 20= Buttery and Ling (1974); 21= Schormüller and Weder (1966a); 22= Desjardins et al. (1995); 23= Petersen et al. (1998); 24= Waterer and Pritchard (1984b); 25= Waterer and Pritchard (1985); 26= Self and Swain (1963); 27= Swain and Self (1964); 28= Ryder (1966); 29= Mazza and Pietrzak (1990); 30= Ulrich et al. (2000); 31= Salinas et al. (1994); 32= Mutti (2000); 33= Grosch (1999); 34= Thybo et al. (2006); 35= Petersen et al. (1999); 36= Mutti and Grosch (1999); 37= Buttery et al. (1973); 38= Coleman et al. (1981); 39= Pareles and Chang (1974); 40= Coleman and Ho (1980); 41= Ho and Coleman (1980); 42= Ho and Coleman (1981); 43= Duckham et al. (2001); 44= Duckham (2002); 45= Oruna-Concha et al. (2002a); 46= Oruna-Concha et al. (2001); 47= Oruna-Concha et al. (2002b)

4.3.3 Boiled Potatoes

The volatile profile obtained from boiled potatoes contains many process-derived compounds that contribute to the overall potato flavour (Buttery et al. 1970; Maarse 1991). Important reactions for the flavour formation are the *Maillard* reaction, *Strecker* degradation and the thermal and enzymatic degradation of fatty acids (Figure 4.2). The *Maillard* reaction results in the formation of methional (Lindsay 1996), which is a key compound of boiled potato flavour (Petersen et al. 1998). Autooxidation (Frankel 1998) and enzymic (hydroperoxide lyase) action on hydroperoxides derived from linoleic and α-linolenic acids (Gardner 1995) produce a range of flavour-active volatile aldehydes, ketones, alcohols and alkyl furans. Pyrazines, pyridines, pyrroles, thiophenes, thiazoles and terpenes present the other major classes of cooked potato volatiles (Coleman and Ho 1980; Taylor et al. 2007).

Ulrich et al. (2000) have identified in total more than 140 volatiles, which contribute, more or less, to the aroma impression. Maga (1994) and Salinas et al. (1994) have identified approximately 150 volatile compounds in boiled potatoes. The amount of volatiles varies and depends on analysis methods, cooking time, temperature of water, cooking conditions (vacuum or atmospheric system), holding time after cooking, and if analysing, peeled, unpeeled or mashed potatoes. Table 4.2 displays all volatiles specified in the literature with their odour description. A total of 182 compounds were compiled.

Buttery et al. (1970) analysed the volatile oil fraction from potatoes distilled under vacuum conditions at 40°-50° C versus a 3-h distillation under atmospheric conditions at 100 °C. The results showed that under vacuum conditions, the major identified component was 1-octen-3-ol, while in the atmospheric system, the compound 2-pentylfuran was predominant. This shows that the air and the temperature play an important role in the formation of cooked potato volatiles. Nursten und Sheen (1974) had results similar to the findings of Buttery et al. (1970), as far as the major components are concerned. They compared the volatiles associated with the steam distillation of peeled and unpeeled potatoes. Over 30 components were characterised, showing that the essence from unpeeled potatoes generally contained more aromatic compounds and a greater proportion of terpenes in comparison to peeled potatoes. Josephson and Lindsay (1987) identified c4-heptenal in freshly boiled potatoes at high concentrations, which provided a boiled potato-like characterizing aroma and flavour note in the potatoes. C4-Heptenal was formed by a double-bond hydration, retro-aldol degradation of t2, c6-nonadienal, which was also identified in boiled potatoes. Although these compounds occurred at very low concentrations in fresh boiled potatoes, the extremely low recognition thresholds exhibited by these volatiles should allow each of them to influence the overall flavour and aroma of boiled potatoes. The addition of very low levels of c4-heptenal (0.1-0.4 ppb) enhanced the overall earthy potato-like flavour in freshly boiled mashed potatoes. However, addition of c4-heptenal at higher levels, more than 0.7 ppb, resulted in a distinct stale-type flavour.

In addition, several specific compounds have been directly related to desirable flavour and aroma characteristics with methional (Lindsay 1996), methoxypyrazines (Murray and Whitfield 1975) and the lipid degradation product, *cis*-4-heptenal (Josephson and Lindsay 1987), all reported to exhibit “a cooked potato odour.” According to Ulrich et al. (1998) the characteristic impact compounds of the boiled potato aroma are methional, diacetyl and alkyl pyrazines. The compounds 2,4-nonadienal, 2,4-decadienal and 2-pentyl furan are among the off-flavour compounds in boiled potatoes.

Mutti and Grosch (1999) screened the potent odorants of boiled potatoes of the cultivar Sieglinde with three different sensory analyses. In addition to the aroma extract dilution analysis (AEDA) and aroma extract concentration analyses (AECA), which both detect only the medium and low volatile odorants, gas chromatography/olfactometry of static headspace samples (GCO-H) was used for the identification of the highly volatile odorants. Altogether 45 compounds were found of which 42 were identified. After boiling under conditions usual for domestic consumption, the volatiles were isolated from the potato sample and then separated into the neutral/basic and acidic fractions. In the neutral-basic fraction, 29 odorants were found in the flavour dilution (FD)-factor range of

8 to 512. The FD-factor for a compound is defined as the ratio of its concentration in the initial extract to its concentration in the most dilute extract, in which odour was detected by High Resolution gas chromatography (HRGCO) (Milo and Grosch 1995). The most odour-active compounds with the highest FD-factor were methional (FD-factor 256) and trans-4,5-epoxy-(E)-2-decenal (FD-factor 512) (Mutti and Grosch 1999). Further important flavour compounds with an FD-factor of 64 were 2-acetyl-1-pyrroline, dimethyltrisulphide and 2,3-diethyl-5-methylpyrazine. The next FD-factor level of 32 appeared with 1-Octen-3-one, 1,5-octadien-3-one, 2-nonenal, 2,6-nonadienal, 2-nonenal, 2,4-nonadienal and 2,4-decadienal, which were formed by peroxidation of linoleic acid or linolenic acid. After the AECA method methional and epoxydecanal were revealed as the most potent odorants of boiled potatoes. This result was in agreement with that of AEDA. In the GCOH analysis, the odorants methanethiol and 2-Isopropyl-3-methoxypyrazine were additionally detected.

The comparison of the aroma of the original potato and the imitation resulted in satisfying agreement. This successful imitation of the boiled potato aroma shows that these five compounds mainly create this aroma. The rest of identified compounds serve to round or rather to intensify the boiled potato flavour. The results demonstrate that only odorous substances are involved in boiled potato flavour, the intensity of which can be enhanced by adding table salt (Grosch 1999; Mutti 2000).

According the analysis of Mutti and Grosch, the compounds methanethiol, 2,3-diethyl-5-methylpyrazine, 2-isopropyl-3-methoxypyrazine as well as methional showed high FD-factors and contributed to the typical boiled potato flavour.

4.3.4 Baked Potatoes

Traditionally the potato is intact before baking at a relatively high temperature for approximately one hour, which results in subtle but pleasant flavour changes in a potato. A potato with higher solids content is used for baking, and the outer layer and skin of the potato are retained during preparation (Coleman and Ho 1980). The potato is in this case the only source of thermally generated flavour precursors. In other processed potatoes (boiled potato, chips, French fries) some of the flavour precursors and compounds are derived from the cooking medium (oil, fat, water with table salt) or through enzymatic and oxidative attack by the peeling or slicing of potatoes (Deck et al. 1973; Maga 1994). Nevertheless, the baked potato flavour has a very mild but extremely complex flavour (Coleman and Ho 1980).

Since potatoes are usually baked intact, one could suggest that the potato skin serves as a trap to hold the resulting thermally produced volatiles within the potato. Certainly, it is evident that during baking some of the volatiles produced do escape into the atmosphere, but this proportion has not been reported in the literature. That is also the reason why some consumers prefer to wrap aluminium foil around potatoes before baking. Maybe the foil wrap retains a greater portion of the volatiles generated, so that they can be absorbed into the potato instead of being lost to the atmosphere (Maga 1994). However, in the literature there are no findings concerning the use of foil during the baking process. Mostly, after baking, the potatoes were removed from the oven, than wrapped in foil, and left to stand for some minutes (Oruna-Concha et al. 2002a; Oruna-Concha et al. 2002b).

Up until 2000, only few papers dealt with the flavour of baked potato (Buttery et al. 1973; Pareles and Chang 1974; Coleman and Ho 1980; Ho and Coleman 1980; Coleman et al. 1981; Ho and Coleman 1981; Mazza and Pietrzak 1990). All volatiles of baked potato are listed in Table 4.2. The compiled references identify 392 compounds in baked potatoes.

One of the earliest studies, reported by Buttery et al. (1973), commented that the skins from baked potatoes had a greater ratio of pyrazines to aldehydes than the whole baked potato. In contrast, the volatiles from inside of the potato had a greater ratio of aldehydes to pyrazines. They held that both temperature and moisture conditions were more appropriate for pyrazine formation in the skin fraction compared to the potato interior. From their point of view, the most important compounds were 2-ethyl-3,6-dimethylpyrazine, methional, 2,4-dienal and 2-ethyl-3,5-dimethylpyrazine. In their opinion, of the pyrazines, 2-ethyl-3,6-dimethylpyrazine is one of the major contributors to baked potato aroma.

This is in accordance with the results of Pareles and Chang (1974) (see Table 4.2). They separated the volatile flavour compounds in baked potatoes into acidic, neutral, and basic fractions and found that the basic and neutral fractions had the most characteristic baked potato aroma. They concluded that 2-ethyl-3,6-dimethylpyrazine was one of the most important compounds contributing to baked potato aroma. However, it was deduced that a combination of 2-isobutyl-3-methylpyrazine, 2,3-diethyl-5-methylpyrazine, and 3,5-diethyl-2-methylpyrazine had a much more characteristic baked potato aroma than did any single compound. Beside the pyrazines, the compound 5-methyl-2-furaldehyde was identified in their investigation, which might also contribute to the total flavour of baked potatoes.

Coleman, Ho and Chang (Coleman and Ho 1980; Coleman et al. 1981) also pointed out that in addition to pyrazines, thiazoles contribute to the baked potato flavour. A round thirty pyrazines and three thiazoles were identified, whereof many of them have never been reported as volatile flavour components of baked potato or potato products before. The results of their research indicated that a natural baked potato flavour is not due to a single compound, but is the result of the mixture of a number of components. The compounds are considered as important contributions to the earthy, nutty, baked, sweet earthy, potato, and baked potato-like aromas. 2-Ethyl-6-vinylpyrazine was described as buttery, baked, and potato-like. 2-Ethyl-3-methylpyrazine produces a pleasant earthy und nutty note to the total flavour (Coleman and Ho 1980; Coleman et al. 1981). 2-Ethyl-3,6-dimethylpyrazine possesses an earthy, baked potato-like aroma, and is according the scientists a very important compound to influence the flavour. Furthermore they found out that there are more pyrazines in baked potatoes than in other forms of cooked potatoes because of the presence of baked potato skins (Coleman and Ho 1980). In a study by Koehler et al. (1969) it was shown that for an appreciable rate of pyrazine formation temperatures greater than 100° C are needed.

On the basis of these thus-far mentioned studies, it would appear that the most important flavour compounds of baked potato are pyrazines, special 2-ethyl-3,6-dimethylpyrazine, methional, oxazoles, thiazoles and furanone.

As of 2000, other studies followed. These were engaged mainly in effects of cultivars (Duckham et al. 2001; Oruna-Concha et al. 2001; Duckham et al. 2002; Oruna-Concha et al. 2002a), storage times (Duckham et al. 2002) and preparation possibilities (Oruna-Concha et al. 2002b) on the volatile flavour components in baked potatoes.

Oruna-Concha et al. (2001) were the first who compared the volatile flavour components of different potato cultivars after baking. They analysed the volatile compounds from the skin and flesh of baked potatoes and compared the levels isolated from four potato cultivars growing at different sites. The potatoes were baked in their skins prior to separating the skin and flesh. The volatile composition of the skin and flesh of baked potatoes varies quantitatively and qualitatively among cultivars grown at different sites. Sugar degradation and/or the *Maillard* reaction is the major source of volatiles in skin, due largely to pyrazine while, in the flesh, lipid degradation products were also important.

Duckham et al. (2001) analysed the volatile flavour components of the flesh of potatoes following baking. For this study, a wider range of cultivars was used than has been ever reported so far. Their research revealed that lipid oxidation and the *Maillard* reaction are the major sources of flavour compounds of baked potato flesh, and that other components like sulfur compounds, methoxypyrazines and terpenes are also present at lower levels. According to their analysis, compounds like 2-isobutyl-3-methoxypyrazine, 2-isopropyl-3-methoxypyrazine, β-damascenone, dimethyl trisulfide, decanal and 3-methylbutanal contribute most to baked potato flavour.

4.4 The effects of variety, agronomic and preparation measures on the volatiles compounds and quality of raw, boiled and baked potatoes

The flavour of food plants is variety-specific, defined genetically, but the natural habitat determinants, the cultivation (including fertilization) and the stage of maturation could also have an influence on the forming of flavour components (Doms and Timmermann 1982). Furthermore, the storage conditions have an effect on the chemical composition of raw potatoes and on the sensory quality and aroma composition of boiled potatoes (Thybo et al. 2006). Even preparation conditions like boiling, conventional baking or microwave baking have an impact on the volatile compounds and ultimately on the sensory quality.
The specific effects and their interference with the volatiles are specified in the following.

4.4.1 Raw Potato

4.4.1.1 Potato variety

It is clear that plant genetics influence flavour (Paillard 1981). The genetic composition determines enzyme systems and their activity in flavour formation (Heath and Reineccius 1986). It is also known that varietal differences in flavour are due to quantitative differences in flavour composition rather than qualitative differences. But there are no comparable analyses about raw potatoes concerning differences of volatile compounds.

4.4.1.2 Fertilization

In how far a different nutrient supply can influence the flavour of potatoes has so far attracted only little interest. Hunnius et al. (1978) and Nitsch and Klein (1983) reported the negative changes of taste value of table potatoes (low mealiness, high moisture, poor taste) as a result of a high fertilization with nitrogen. Khan et al. (1977) showed via a pot experiment the influence of nutrient combinations on the spectrum of volatiles in raw potatoes. Both analyzed varieties, Grata and Saturna, include the following compounds: acetaldehyde, propanal, 2-butanon, pentanal, hexanal, heptanon, heptanal, 2-hexenal, octanal and nonanon. Differences in fertilization with nitrogen, phosphoric acid, potassic and magnesium cause a deferment in the spectrum of identified volatiles. High fertilization amounts with nitrogen resulted in a decrease of acetaldehyde and propanal. In contrast, quantities of hexanal, heptanon, 2-butanon, 2-hexenal and octanal increased. Neither a positive nor a negative influence of different nitrogen fertilization levels on pentanal and nonanon could be detected. Higher additions of potassium benefit the volatiles of tubers with the exception of 2-hexenal and nonanal. An elevated fertilization with phosphate had a positive effect of acetaldehyde, pentanal, hexanal, heptanon, 2-butanon and octanal. No differences were observed after different phosphate applications by propanal, heptanal and nonanon, but a higher phosphate application caused a decrease of 2-hexenal. An increase in magnesium application induced a higher content of heptanon in both cultivars. No other effects of magnesium fertilization were assessed. The results were partially confirmed by Fischer (1991). He used a pot experiment to analyze the effect of various amounts of nitrogen and potassium on the composition of the aroma of native potatoes. Fischer (1991) found an increase of 2-hexenal, heptanal and 2,4-decadienal due a higher nitrogen application. A rising potassium application resulted in an increase of pentanol and 2-hexenal. He postulated that fertilization influenced the amount and type of lipid in the tuber, which in turn was the precursor for the compounds identified. How far climate factors can also contribute to differences in volatile compounds is under discussion.

4.4.1.3 Storage conditions

Under proper conditions, potato tubers can be stored for long periods of time before they are processed or consumed. Waterer and Prichard (1985) compared the volatiles produced by healthy tubers versus tubers that had been intentionally punched with needles. Volatiles were analyzed daily for six days. Wounded tubers produced 2-3 times more volatiles in total than the non-damaged control. Especially an increase of 15 compounds like methanol, ethanal, 1-propanal, 2-propanone, 1-propanol, 2-butanol, 2-butanone, 1-butanal, 2-methyl-1-propanal, 1-butanol, and 3-hydroxy-2-butanone were measured. All compounds except 3-hydroxy-2-butanone were found in normal tubers. Water and Prichard (1985) explained this with a higher metabolic activity associated with the wounds.

The content of volatile compounds increases and the quantitative ratios change when potato tubers are infected with pathogens. Waterer and Prichard (1984a) compared the volatiles produced by non-infected and infected tubers stored in plastic bags. They inoculated potato tubers with the bacterium *Erwinia caratovora* var. *carotovora.* Healthy tubers produced volatiles at a relatively low and constant rate. In the volatile profiles of the infected tubers a wide range of short chain alcohols and carbonyls were identified. During the development of the *E. carotovora* infection there was a general increase in the concentration of the individual volatiles, but certain compounds increased more than others. Lowering the temperature slowed disease development, resulting in decreased volatile production and changes in the pattern of volatile output. Wounding of potato tubers caused a general increase in volatile production by the tubers. In total, 14 volatile compounds (5 unidentified) were detected in the infected tubers. These included u.a. ethanol, methanol, ethanal, propanal, 1-propanol, 1-butanol, 2-butanol, 2-methyl-1-propanol, 2-propanone (acetone) and 3-hydroxy-2-butanone.

4.4.2 Boiled Potato

4.4.2.1 Potato variety

Only little information is available concerning the typical cooking flavour influenced by varieties. Ulrich et al. (1998) analysed the aromatic compounds of two varieties, the genotype “St1.365” and cv. “Adretta”. The isolated volatiles were identified by GC-olfactometry-method. The obtained aromagrammes, including the aroma key compounds, were compared with the results of the sensory evaluation. The sensory evaluation was carried out by a trained panel consisting of 15 members. Methional (3-methylthio-propanal), with the typical potato smell, was the compound with the highest peak in both varieties. The results showed that Adretta has an increased buttery or sweet caramel-like impression caused by 2,3-butanedione (diacetyl). The genotype St. 1.365 is characterized by high boiling volatiles, some identified as dienals with fatty and rancid odour impressions. The sensory profiles corresponded very closely to the analytical results. Adretta emits an increased sweet impression caused by diacethyl. The St 1.365 is evident in off-flavour note impressions like metallic and musty notes produced by dienals.

Thybo et al. (2006) proved the effect of cultivars on the aroma composition of cooked pre-peeled potatoes. The cultivars Berber, Arkula, Marabel, Sava, Folva and Agria were grown in three replicates on a fine sandy soil. A PCA (Principal Component Analysis) of the aroma components indicated that the variation of most of the aroma components was caused mainly by the effects of cultivar. In Sava, Folva and Agria higher intensities of methional, linalool and cymene and low intensity of nonanal and decanal were detected. In contrast, high intensity of nonanal and decanal was found in the cultivars Marabel and Berber, with a high intensity of rancidness and low intensity in potato flavour. This result showed that the cultivars Sava, Folva and Agria performed better with methional, described with a distinct boiled potato odour, than Marabel and Berber with their identified compounds contributing with a rancid and fatty odour.

4.4.2.2 Fertilization

It is known that fertiliser and method of application generally influence the basic nutrients of the boiled potatoes (Neuhoff et al. 1999; Stühring 2004; Haase et al. 2005; Peine 2005; Ceylan et al. 2006; Sandbrink and Grocholl 2006; Singh et al. 2008). Because the volatile aroma compounds derive from the basic nutrients, it could be assumed that the flavouring compounds would be affected by fertilization, too. However, there are hardly any findings in this area.

Thybo et al. (2002) analysed the effect of six different organic treatments of the sensory quality of potatoes. The cultivar Sava was grown under six organic treatments with three field replicates (18 samples) in sandy loam. Cattle slurry or cattle deep litter was applied corresponding to an equal supply of total nitrogen. The manure was applied 7-8 days before planting. The slurry was either placed under the seed potatoes, ploughed in with the straw of the preceding rye crop left in the field or ploughed in alone. The results showed no significant effects of the flavour of boiled potatoes manuring with different organic fertilizers.

4.4.2.3 Storage time after boiling

When potatoes are boiled and then chill-stored, they rapidly (i.e., within hours) change their flavour. This rather undesirable flavour can be described as cardboard-like (Petersen et al. 2003). It is a result of lipoxygenase activity released from disrupted cells during the peeling process and the first part of the boiling process (Petersen et al. 1999). Petersen et al. (2003) determined the lipoxygenase activity in raw and fresh boiled potatoes and in boiled potatoes refrigerated until the next day. All potatoes underwent a long-term storage at 4° to 5° C at 90 to 95% relative humidity. All potatoes were peeled manually before boiling. Each month (from November until May) potatoes were analysed for lipoxygenase activity and their aroma profile was measured in raw freshly boiled potatoes and in potatoes that were refrigerated for 24 h/5° C after boiling. The most off-flavour compounds in all three versions were pentanal, hexanal, 2-octenal, 2-nonenal, 2,4-nonadienal and 2,4-decadienal and two typical potato aromas, methional and 2,6-nonadienal. Except 2-nonenal, all compound concentrations were significantly higher in the boiled/24 h-stored potatoes than in raw or the freshly boiled. The two 2,4-alkadienals were in fact only detected in the boiled/24 h-stored potatoes. Petersen et al. (2003) could not detect nonanal, and 2-nonenal did not change significantly during 24 h storage of boiled potatoes. However, they found out that the typical potato aroma compound 2,6-nonadienal disappeared during 24 h storage of boiled potatoes and the concentration of methional showed a tendency to decrease. On the other hand, Grosch (1999) realised an increase of the concentration of methional with its typical boiled potato flavour and 2,4-decadienal with fatty notes about 320% and 283% within 2 hours. However the compounds with an earthy note 2,3-diethyl-5-methylpyrazine and 3-isobutyl-2-methoxypyrazine decreased. The warm-holding induced a negative modification of the boiled potato flavour.

De Fielliettaz Goethart et al. (1985) studied the influence of keeping potatoes warm on their organoleptic quality. One or two temperatures and three or four different times, up to 3 h, were applied. It appeared that the decrease in quality as the result of keeping warm is, in most cases, the result of an increase in off-flavours and a decrease in positive flavour aspects. The panel concluded that boiled potatoes should not be kept warm for longer than half an hour, and certainly not longer than 1 h.

4.4.3 Baked Potato

4.4.3.1 Potato variety

Oruna-Concha et al. (2001) reported about the volatile flavour compounds of the skin and the flesh (analysed separately) of four potato cultivars after baking. The varieties Cara, Nadine, Fianna and Marfona were selected. The concentrated extracts were analyzed by GC-MS. The volatiles were identified and classified according to their origin, that is, lipid, sugar degradation (SD) and/or *Maillard* reaction (MR) not involving sulphur amino acids, sulphur compounds, methoxypyrazines, and other compounds. They observed quantitative and qualitative differences between samples isolated from flesh and skins, and among cultivars grown at different sites in the U.K. SD and/or MR was by far the main source in skin of all cultivars (71-78 % of the total amount) except Nadine (28 %), with pyrazines contributing from 56 % (Nadine) to 73 % (Cara) of amounts in this group. In every cultivar 2,5- and/or 2,6-dimethylpyrazine was the most abundant representative compound. The amino acid asparagine comprised the largest component in pyrazine formation (Hwang et al. 1995). Nadine possessed the lowest level of asparagines, and this may account, partially, for the low levels of pyrazines observed. Methional with its typical cooked potato aroma could not be identified. Maybe it was masked by 2,5-and/or 2,6-dimethylpyrazine (Oruna-Concha et al. 2001). The methoxypyrazine 2-isopropyl-3-methoxypyrazine was only present in Marfona. This compound is of particular interest due to its very low odour threshold value of 2 ng/L and because it was previously identified in raw, boiled and baked potatoes. Buttery and Ling (1973) have suggested that it stems from bacteria formed in the soil and can be absorbed into the tuber. But they discovered that the similar compound 2-isobutyl-3-methoxypyrazine is synthesized by bell peppers, to which the potato is closely related. Because 2-isopropyl-3-methoxypyrazine was only found in one cultivar, it would appear that there may be differences among the cultivars examined in their ability to synthesize this compound. In the opinion of Oruna-Concha et al. (2001), another reason for the synthesis could be the differences in cultural conditions. Solavetivone, a sesquiterpene, was identified in all four cultivars. Compared to the other cultivars, a relatively high level was analysed in the skin of the cultivar Nadine. Because solavetivone is a marker of stress metabolite (Zacharius and Kalan 1984), Oruna-Concha et al. (2001) suggested that Nadine tubers were under stress during storage, although they and all the tubers of the other three cultivars appeared to be in good condition. One could argue that Nadine may have been biochemically less stable than other cultivars.

The lipid and SD and/or the MR were responsible for the volatile formation in the flesh. The lipid degradation was the prevalent source of volatiles in Cara (93 %), in Fianna (75 %), but only 15 and 19 % of the volatiles in Nadine and Marfona. Especially levels of pyrazines were much lower in the flesh, and those compounds that were identified, according to Buttery et al. (1973), migrated from the skin, where the higher temperature and lower water activity (compared to the interior of the tuber) located during baking would favour their formation. Furthermore, the compounds 2,4-decadienal, 2-nonenal and methional appear to be the most important contributors to flesh aroma.

Oruna-Concha et al. (2002a) compared the volatiles in the flesh of eight cultivars of potatoes after microwave baking. The cultivars Marfona, Desiree, King Edward, Fianna, Nadine, Pentland Squire, Saxon and Cara were grown in the same field in the U.K. Sixty of the 80 volatile compounds identified in this study were lipid-derived. Prominent compounds present in all cultivars included hexanal, nonanal, decanal, benzaldehyde and 2-pentyl-furan. 2-Isobutyl-3-methoxypyrazine was presented in identifiable amounts in only the cultivar Desiree. Alkylpyrazines followed from the MR were not identified in the microwave-baked potatoes. Duckham et al. (2001) came to similar conclusions. They analysed the baked potato flesh of eleven cultivars, which were grown on the same field and were baked in a conventional oven. The cultivars were partially equal to those of Oruna-Concha et al. (2002a): Nadine, Golden Wonder, Fianna, Estima, Cara, Saxon, Kerr’s Pink, Maris Piper, Desiree, Marfona and Pentland squire. Marfona gave the highest absolute yield and relative yield (77 %) of compounds formed by the MR and/or (SD) while yields were lowest for Cara (25 %). These results agree with those of Oruna-Concha et al. (2002a), who also found the highest yield of compounds by the MR and/or SD in Marfona and the lowest in Cara. The most abundant representatives in both studies were the *Strecker* aldehydes 2- and 3-methylbutanal, which were identified in every cultivar and contributed 75-96 % of the volatiles in this category. However, statistically significant differences were observed in the levels of both aldehydes between the cultivars. Furthermore, only one or more pyrazines were identified in only six of the eleven cultivars, most representatives Golden Wonder (Duckham et al. 2001). The formation of pyrazines is facilitated by high temperature and intermediate moisture; conditions that concerned in the outer layer of the potato tuber during baking. The analysed pyrazines may have migrated from the outer layers of the potato towards the centre during baking (Buttery et al. 1973). Also methional was detected in only five cultivars with the highest level in the cultivar Nadine. In contrast, dimethyl disulphide, which can form from methional, was present in all cultivars and dimethyl trisulphide were found in all except Golden Wonder (Duckham et al. 2001).

In summary, it could be retained that the lipid and the MR and/or SD are the major sources of compounds in all cultivars. However, each potato cultivar possessed a unique profile of volatile compounds.

4.4.3.2 Storage conditions

The study of Duckham et al. (2002) examined the effects of cultivar and storage time on amounts of selected volatile flavour components of the flesh of potatoes following baking. They chose the five cultivars Estima, Saxon, Golden Wonder, Kerr’s Pink and Desiree, which were grown on different sites in the U.K. Tubers were stored at 4°C for 2, 3, and 8 months and baked in a conventional oven. The flavour compounds were isolated by headspace method and analysed by GC-MS. More than 150 compounds were detected. There was a significant increase in total amounts of compounds between 2 and 3 months, and between 3 and 8 months storage. With storage time, the total amounts of compounds derived primarily from lipid increased, and there were differences for each storage time interval. The amounts of the lipid-derived aldehyde hexanal, heptanal, nonanal and decanal all increased significantly between 3 and 8 months. By contrast, 2-heptanone, 1-octen-3-ol and butanedione, which are also originated from lipids, were significantly lower after 8 months of storage compared the other storage times. The levels of *Maillard*/sugar-derived compounds were significantly higher after 8 months as compared to 2 and 3 months of storage. Between 2 and 3 months, methypropanal, 2-methylbutanal and 3-methylbutanal showed no significant increase, followed by a significant increase between 3 and 8 months. Methional was the only compound in this study that showed a significant storage time effect, the amounts decreased between 3 and 8 months.

4.4.3.3 Preparation conditions (conventional baking, microwave baking, boiling)

Heat and mass transfer characteristics of foods cooked by microwave radiation are different from those associated with conventional baking (Van Eijk 1994). Potatoes are more rapidly baked in a microwave oven (e.g., ~ 10 min) than in a conventional oven (~ 1 h) (Wilson et al. 2002b). There are some studies compared the flavour of conventionally and microwave baked potatoes (Eheart and Gott 1964; Bowman et al. 1971; Maga and Twomey 1977; Brittin and Trevino 1980; Oruna-Concha et al. 2002b). In a study by Maga and Twomey (1977), a trained panel ranked four potato cultivars (respectively baked conventionally and baked by microwave) from the best to worst on the basis of external and internal appearance, aroma and flavour. It could be shown that in all cases microwave baking came off badly, and the trained panel preferred the conventionally baked potatoes. Brittin and Trevino (1980) evaluated the flavour of conventionally and microwave-baked potatoes using both a 10-member trained panel and a 120-member consumer panel. The trained sensory panel ranked the microwave-baked tubers lower while a consumer panel showed no significant differences for preferences or acceptability. Using GC-MS, Oruna-Concha et al. (2002b) determined the effects of boiling, conventional baking and microwave baking on the profiles of flavour compounds of two potato cultivars (Estima and Maris Piper). Peeled and sliced tubers were boiled, while intact potatoes were baked in their skins. Regardless of cooking procedure, main sources of flavour compounds resulted in lipid degradation and from the MR and/or SD. The proportion of lipid-derived compounds to the proportion of sugar- and/or *Maillard*-derived compounds decreased from 8.5-9.1 (boiling) to 2.7-3.4 (microwave baking) and to 0.4-1.1 (conventional baking). The total levels of lipid-derived compounds in boiled potatoes were 1.2-2.1-fold higher than those that had been prepared in the microwave and 1.5-3.2-fold higher than those that had been conventionally baked. Hexanal, 2-heptenal and 2-pentylfuran were higher after boiling, but 2-nonenal and decanal were the highest following microwave baking. Higher amount of hexanal and 1-octen-3-ol were found after baking conventionally than in the microwave oven. The levels of the lipid-derived 2-methylfuran, 2-pentylfuran, 3-hexanone and 1-octen-3-ol were significantly higher after boiling. The total number of compounds derived from SD and/or the MR was always highest for conventionally baked potatoes and lowest for those that had been boiled. The potato flesh of microwave-baked potatoes gave the weakest isolates of volatile compounds.

These quantitative and qualitative differences for the flavour compounds created by the three cooking procedures may be partially attributed to the variations in heat and mass transfer processes that occur.

During baking in a conventional oven, heat is transferred into the potato at its surface and the surface temperature increases to 100°C. The rate of the heat transfer is limited by heat loss through water evaporation and by the reduced thermal conductivity of the dried skin layer (Wilson et al. 2002a). Finally, the surface temperature increases above 100°C, a crust develops, further evaporation of water takes place and the 100°C isotherm moves towards the centre of the tuber. Water loss during baking amounts for ~200 g kg^{-1} of the original mass of the tuber and increases linearly with cooking time. From the outer 3 mm of the tuber is the most of moisture lost (~ 57 %) and the crust rapidly becomes a low-moisture zone. During boiling, the water loss from the tuber is marginal and the 100°C isotherm migrates more rapidly towards the centre of the tuber than during conventional baking (Oruna-Concha et al. 2002b).

The heating method during microwave baking is quite different from those for other cooking procedures; short baking time and the outer surface, which, owing to evaporative cooling, remains at a lower temperature, and, in contrast to conventional baking, forms no crust (Oruna-Concha et al. 2002b). Baking in the microwave resembles oven baking in that there is substantial evaporative loss of water, but the conversion of microwave energy into heat is dispersed (Wilson et al. 2002b). The input of energy is not spatially uniform, but the degree of non-uniformity varies with the shape and dimensions of food material (Zhou et al. 1995). Oruna-Concha et al. (2002b) could show that the amount of moisture lost during microwave and conventional baking were about the same, but in the tubers prepared in microwave oven the loss of water was uniformly throughout the tuber. This mechanism of water loss, which in their opinion could result in losses of flavour compounds through co-distillation, plus evaporative cooling at the tuber surface could account for the lowest of total volatiles in the isolates prepared from microwave-baked potatoes. The moisture is an important factor influencing the MR, and the reduced moisture levels in potatoes baked by both methods most likely played a key role in the observed levels of components formed via this pathway. In the conventionally baked tubers, an outer crust was formed, an area of low moisture content with a temperature between 100°C and the set oven temperature (190°C). Such a crust was not noticed in the microwave-baked potatoes, but the levels of the *Maillard* products were higher than in boiling and this must be the consequence of the reduced moisture level in the tuber caused by microwave baking. In an investigation by Van Eijk (1994), the low moisture content and the high temperature of the crust that develops at the surface of the tuber during conventional baking, together with the relatively long cooking time, abet the MR in comparison to microwave baking.

Both baking methods, which had lower amounts of lipid degradation products than boiling, led to a more rapid temperature increase in potato tissue, compared to boiling, and lipoxygenase is expected to make a smaller contribution to flavour development in intact tubers. Thus it is presumed that, the majority of the lipid-derived components in baking potatoes resulted by thermal degradation of lipid rather than enzymatic oxidation.

4.5 Conclusions

Large numbers of volatile compounds were identified in raw, boiled and baked potatoes. These can be considered as products of lipid or sugar degradation and/or *Maillard* reaction/lipid interactions. Lipid oxidation products of unsaturated fatty acids are the major source of volatiles in raw potatoes due to the relatively high lipoxygenase content. Important reactions for the flavour formation in boiled potatoes are the *Maillard* reaction, the Strecker degradation and the thermal and enzymatic degradation of fatty acids. The volatile composition of the skin and flesh of baked potatoes varies quantitatively. Sugar degradation and/or the *Maillard* reaction is the major source of volatiles in skin, due largely to pyrazine while, in the flesh, lipid degradation products were also important. The desirable heated potato flavour in boiled and baked potatoes seems to centre around pyrazines in various combinations that result in a typical earthy, potato-like flavour.

Because potato tubers are only consumed after cooking or baking, there are only few results on the volatiles in raw potatoes. The small number of studies deals with volatiles after tuber damage or microbial attack. However, there would be an advantage to identifying the volatiles in the raw product. By comparing these with those of processed potatoes, positive or negative impacts by the raw product on the final product- flavour could be determined. This information could serve for breeding new varieties with certain properties, which eventually comply with consumer demand.

The impact of agronomic measures on the volatile compounds in raw, boiled and baked potatoes was not taken into intensive consideration thus far. Especially in view of the volatiles in different varieties and in different agricultural systems (ecological, conventional), fertilization and storage there are hardly findings.

This stresses the future need for research, in particular regarding the effects of agronomic measures on the volatile compounds and their influence on the sensory quality of raw as well as processed potatoes.

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5 General discussion

For health concerns, the demand for organically grown potatoes has gradually increased worldwide. Also processing is a segment of the organic food industry that looks set to grow significantly over the next few years (Smithson 2007). Due to increasing demand for convenience-products, organic potato cultivation for industrial processing into French fries or potato crisps will be a new source of income for German growers (Kuhnert et al. 2004). The quality requirements for organic table potatoes and raw potatoes for processing are high and differ from each other. The processing industry requires high portion of larger tubers for French fries and crisps (Schuhmann 1999; Böhm 2003; Haase et al. 2007b), ranges and thresholds for starch, tuber dry matter (DM), as well as for the concentration of reducing sugars (glucose and fructose) (Putz and Lindhauer 1994; Schuhmann 1999). Besides health, in particular, better flavour and texture frequently motivates consumers to purchase organic table potatoes. Flavour formation in potatoes is a complex trait and results from the interaction of volatile compounds and soluble cellular constituents. The soluble compounds define the basic taste parameters, sweet, sour, salty or bitter (Taylor et al. 2007). In addition to the most predominant senses smell and taste, also sight (colour and appearance), tactile sensations (texture and mouth-feel) and pain (pungency) are decisive for flavour sensation (Reineccius 1999; Kays and Wang 2000; Belitz et al. 2008). Organic potatoes are subject to the same requirements on sensory qualities as conventional potatoes, but the production costs for organic potatoes are roughly 50 % higher and the yields 50 % lower (Pimentel 1993; Yue et al. 2010; Böhm et al. 2011). Thus, for organic table potatoes as well as for potatoes to be processed into French fries or crisps, both, high tuber quality and above-average yields are essential factors for the commercial profit of the growers. To meet these market demands, a continuous optimization of crop management is required by farmers. New and more extensive approaches to improving the quality of organic potatoes are necessary for increasing sales.

The aim of the present thesis was to investigate if cultivar choice, agronomic measures such as preceding crops, application of organic fertilizer, irrigation, storage conditions or different growing conditions such as weather and soil properties influences the quality-determining properties of organic table potatoes and organic potatoes to be processed into French fries or crisps. The investigation includes one field study, one field experiment and a literature study. In the field study in chapter 2 the influence of cultivars (cvs Princess, Nicola and Ditta), different selected agronomic measures (preceding crop, organic fertilizer, irrigation, storage) and weather and soil conditions on yield, starch and nitrate concentrations and sensory quality (peeling ability, yellowness, mealiness, sweetness, bitterness) of cooked organic potatoes in the skin were evaluated. The effect of different defoliation systems (cutting, mulching and a combination of cutting and mulching) of the pre-crop ryegrass-clover on total tuber and size-graded yields and selected quality attributes of organically grown potatoes, destined for processing into French fries (cv. Agria) or crisps (cv. Marlen), were conducted in a field experiment in chapter 3. Furthermore, the influence of additional slurry fertilization and a 4-month of storage on these parameters were investigated. The literature study in chapter 4 deals with the development and identification of volatile compounds in raw, boiled and baked potatoes and their relevance for potato flavour. It outlines the influence of agronomic measures, such as cultivar choice, fertilization and storage, as well as the influence of diverse preparation possibilities on the formation of volatiles.

Different cultivar characteristics, degree of maturity, method of cultivation, amount and kind of fertilizers, site and soil, irrigation, seasonal variations, temperature and global radiation during growth as well as length of growth period influence yield and quality formation of raw tubers and can therefore affect the sensory quality (Heinze et al. 1955; Paillard 1981; Roth 1987; Kolbe 1990; Hospers-Brands et al. 2008).

A genetic-influence of cultivar on yield formation was only observed in processing potatoes in chapter 3. Due to the dry summer (2003) and the specific morphological features of the two different potato cultivars, cv. Agria (reference cultivar for French fries) had (in the first experimental year 2003) with 36 t ha^{-1} a yield advantage of 12 % compared to cv. Marlen (reference cultivar for crisps) with 32 t ha^{-1}. According to the *Federal Office of Plant Varieties* (Bundessortenamt 2004), cv. Agria is assigned to the stem-type of potatoes, while cv. Marlen is assigned to the intertype, with a trend towards leaf-type. With increasing dry stress, the stem-type potato with its high herbal matter has a yield advantage compared to the leaf-type. The leaf-type, cv. Marlen, profits from years with sufficient water supply, as observed in the second experimental year (2004) (Schittenhelm et al. 2006). The yield results are in good agreement with the results of Böhm et al. (2002), who reported comparably high yields of cvs Agria and Marlen. In addition to total yield, tuber size distribution is an important economic factor for different processing directions. In both experimental years the required size-grade of >35 mm with a proportion of at least 60% of tubers >50 mm of the organic French fries industry, was with 52.6 % (2003) and 56.9 % (2004) for cv. Agria nearly reached. In cv. Marlen the portion of tuber yield >50 mm was 28.9 % of total yield in 2003 in contrast to 53.6 % in 2004. These results can be explained by the specific morphological features of both cultivars and the different weather conditions in both years. Haase et al. (2007b) also reported that cultivar mainly effect tuber yields graded for crisp and French fries production. Starch concentrations are genetically determined and vary significantly dependent on cultivar (Cottrell et al. 1995; Haase and Plate 1996; Jansen et al. 2001). Table potatoes are distinct between waxy (9-12 % in FW), predominantly waxy (12-15 % in FW) and mealy cultivars (15-18 % in FW) (Wölfel 2002). Higher starch concentrations in tubers for processing into French fries (14-18 % in FW) and crisps (16-20 % in FW) are required (Böhm 2003). All three table potatoes in the present study in chapter 2 are according to the description list of cultivars of the *Federal Office of Plant Varieties* (Bundessortenamt 2011) listed as waxy cultivars. With 12.0 % for cv. Ditta and 9.8 % for cv. Princess, starch concentrations in both cultivars were in the classified range for waxy cultivars. With 13.3 % for cv. Nicola, tuber starch concentration was above the values for waxy cultivars. Higher starch concentrations are favoured by processors to ensure products with acceptable texture and to keep down processing costs by limiting the amount of raw product needed, the cooking time required, and the amount of oil absorbed (Stark and Love 2003). In tubers for processing into French fries and crisps we found in 2003 a starch concentration at harvest, as well as after storage, of 22 % for cv. Marlen (reference cultivar for crisps) and 19 % for cv. Agria (reference cultivar for French fries), which was above the required maximum thresholds. In the following year (2004) this was slightly beneath these values as described in chapter 3. The nitrate concentrations of individual species vary considerably within each maturity group (Kolbe 1990). On average, early cultivars show higher concentrations (190-345 NO_3 mg kg^{-1} FW) compared to late cultivars (140-220 NO_3 mg kg^{-1} FW) (Grassert and Bartel 1987; Hippe 1996; Reents and Tucher 1997). In 2004, the European Union determined maximum nitrate levels of 250 mg kg^{-1} for baby food as well as processed cereal-based foods for infants and young children (European Commission 1997). The nitrate concentrations of the table potatoes (chapter 2) were with 155 mg (NO_3 kg^{-1} FW) for cv. Princess and 97 mg (NO_3 kg^{-1} FW) for cv. Ditta and cv. Nicola significantly beneath the maximum nitrate limits. According to Cunningham and Stevenson (1963) and Stevenson et al. (1964), the heritable trait influenced sugar concentrations. In our study on processing potatoes we found conflicting results. In 2003, cv. Marlen was characterized by lower sugar concentrations than cv. Agria, while in 2004, the opposite was found. The required thresholds of a maximum of 2.5 g kg^{-1} FW reducing sugars for French fries processing were not exceeded in both years. In 2004, tubers from the cut-used variant Marlen had with 2.1 g kg^{-1} FM reducing sugar concentration above the required maximum of 1.5 g kg^{-1} for crisps. Cultivar was shown to have a great market effect on tuber size distribution and starch concentrations, which makes the choice of cultivar the essential tool in cultivation of organic potatoes.

Nitrogen (N) supply and the infestation with *Phytophthora infestans* are the two factors generally stated to be most limiting to tuber yield (Van Delden 2001) and quality formation (Möller 2002) in organic potato cropping. N nutrition in organic potato cropping can be reached either by cultivation of preceding crops, such as legumes (Finckh et al. 2006; Haase et al. 2007a), and/or by application of organic fertilizer (Haase et al. 2007b). There is little information on the impact of preceding crops on potato tuber yield and particularly on potato quality in organic farming systems (Finckh et al. 2006). Haase et al. (2007c) proved the effect of four different preceding crops, winter wheat, oats, peas and alfalfa-grass/clover ley on N use and tuber yield of potatoes destined for processing. They observed higher tuber yields after peas followed by alfalfa-grass/clover ley. In our study in chapter 3 we investigated the influence of the defoliation variants, 3-cutting (3C), 2-cutting+1-mulching (2C+1MU), 3-mulching (3MU) and 1-mulching (1MU) of the preceding-crop ryegrass-clover on tuber yield and quality of potatoes destined for processing into French fries (cv. Agria) or crisps (cv. Marlen) in two experimental years. A significant effect of the defoliation system on tuber yield was only assessed in one year (2003). The 3MU-system resulted in highest total yields (36 t ha^{-1}), followed by the pure cutting-system (3C) (34 t ha^{-1}) and the 2C+1MU-system (33 t ha^{-1}). The highest amount of organic matter (OM) (874 g N m^{-2}) of the crop residues from the 3x mulching ryegrass-clover fields in 2002 may have influenced the retaining capacity of the soil and thus resulted in higher total tuber yields. Dreymann (2005) investigated the impact of different defoliation systems (3-cutting+1-mulching; 2-cutting+2-mulching; 4-mulching) of red clover and grass, discrete or in mixtures, on dry matter, N-accumulation, and yield of subsequent winter wheat. Dreymann (2005) did not found a significant effect on winter wheat yields. Considering the effect of different seed mixtures on winter wheat yield they observed that a 100 % red-clover seed-mixture and 67 % red-clover + 33 % ryegrass seed-mixture had a yield advantage for the 2C+2MU-system compared to the 3C+1MU- and the 4MU-system. In our study tubers from the mulching systems were characterized by lower starch concentrations in both experimental years. It can be assumed that the higher N contents of the crop residues in exclusively mulched systems might lead to a better N-supply, which is known resulting in a decrease of tuber starch concentrations (Hunnius 1972; Neuhoff et al. 1997). Furthermore, mulching led to an increase in tuber K concentrations. This could be explained with the high K contents in red clover and ryegrass. According to Hartmann and Sticksel (2010), K-removal of ryegrass-clover is about 350 kg K ha^{-1}. Hence, in the case of mulching the ryegrass-clover, a high amount of K is available for succeeding crop potatoes. Besides tuber yield, potassium reduces undesirable discoloration in raw and processed tubers (Kolbe 1990). Increasing K supply decreases the levels of undesirable reducing sugars in the processing potatoes (Krause et al. 2005; Gerendás et al. 2007) and thus influences the dark chipping of French fries and crisps and the carcinogen acrylamide. Because mulching had a minor yield advantage (in 2003), the cutting-system appears to be meaningful, even for the farmers without livestock. Growth could be used in biogas plants, resulted digestates can be re-deployed to the farms fields. Cooperation with livestock farms using the cutting clover grass as fodder and in return make manure or slurry available to the stockless farms is possible.

For the production of high quality potatoes in organic farming, the adequate **supply of plant nutrients** is an important factor. Especially N is essential for yield formation (Alva 2004) and affects to a great extent the quality formation such as the nitrate (Wadas et al. 2005) and starch contents (Hunnius 1972; Kolbe 1990), the cooking properties (Möller et al. 2003) and the flavour and texture of potatoes (Fischer 1991; Cieslik 1997). In accordance with the findings of other researchers (Hunnius 1972; Haase 1992; Neuhoff et al. 1997; Möller and Kolbe 2003), we found a decrease of tuber starch concentrations after application of organic fertilizer in both, the field experiment and the field study (chapter 2 and 3). Parallel, the organic fertilization resulted in an increase of the nitrogen content in the processing tubers (chapter 3). In the sensory study a significant negative average correlation between starch and nitrate concentration (r = -0.51) were found with the table potatoes (chapter 2). A reduced photosynthetic capacity induced by weather conditions or by damage of the canopy by *P. infestans* leads to a reduction of starch accumulation in the tubers resulting in a percentage increase of nitrate, a so called concentration effect (Marschner 1984). In numerous studies it could be shown that high N application rates (>150 kg N ha^{-1}) decreased reducing sugar concentration (Swiniarski and Ladenberger 1970; Roe et al. 1990; Kolbe et al. 1995). Haase et al. (2007a) did not find any significant response of reducing sugars after slurry fertilization in their factorial field experiments. They (Haase et al. 2007b; 2007c) indicate that a comparatively very high supply of available N will usually not be achieved in organic potato cropping. Stricker (1975) also found that N supply has only a limited effect on sugar concentrations of tubers for processing. In accordance with these letter findings, we observed no significant effect of slurry application on the reducing sugar contents of the processing potatoes. Only in combination with a 3-way interaction, the fertilization had a significant effect on reducing sugar concentration. With the exception of cv. Agria from the 3C-variant, the fertilized tubers from the cutting-management systems (3C and 2C+1MU) showed lower tuber concentrations of total reducing sugar. The positive response of reducing sugars may be explained by the used cattle manure, which is characterized by high potassium amounts (Peretzki and Heigl 2004). According to Westermann et al. (1994) mineral K application resulted in lower reducing sugar concentrations. This is supported by the higher tuber K concentrations after fertilization in our study. Overall, our results confirm the statement of Putz and Gehse (1975), Hunnius (1977) and Putz and Lindhauer (1994), that the influence of a balanced fertilization on reducing sugars concentration is minor.

Beside fertilization, an adequate **water supply** is essential for yield formation (Miller and Martin 1983). Especially on sandy soils the irrigation led on average to an additional yield of more than 20 % (chapter 2). This result was confirmed by the conducted correlation analysis (r = 0.38). Roth et al. (1987) found an increase in yields in response to irrigation in their field experiments, too. Therefore irrigation is recommended especially on light soils.

According Hospers-Brandes et al. (2008) the **length of growth period** is the determining factor for yield and quality formation. In both field experiments (chapter 2 and 3) the infestation of the potatoes with *P. infestans* resulted in an interrupted and therefore to a shortened growing period. For the table potatoes as well as for the processing potatoes yield losses were observed. The correlation analysis showed a high positive relationship between yield formation and the time interval between planting and the beginning of infestation with *P. infestans* (r = 0.65) (chapter 2). Beside yield, nitrate and starch concentration is influenced by stage of maturity and harvest timing (Gilmore 1905; Kolbe 1990; Reents and Tucher 1997; Thygesen et al. 2001). Especially in tubers from regions suffered under an infestation with *P. infestans*, leading to a shortened growth period, higher nitrate concentrations were measured (chapter 2). The correlation analysis showed a weak negative relationship between the time interval between planting and beginning of *P. infestans* on nitrate concentration (r = -0.25). This is in good agreement with Kolbe (1990), who found that the length of life and quality of the canopy has an effect on the nitrate concentration of tubers. According to Nitsch (2003) an increase of late blight-susceptibility from Grade 3 to Grade 6 led to an approximate doubling of nitrate levels in the harvested tubers. The damage of the canopy leads to a reduction in photosynthesis and the formation of starch in the tubers and so to an increase in nitrate. In the sensory analysis we found that a shortened vegetation period caused by the fungal infection of the potatoes with *P. infestans* also influenced the sensory quality of table potatoes. Due the infestation with *P. infestans* starch synthesis was interrupted, which resulted according the taste panel in lower mealiness and less tuber sweetness. That a shortened growing season leads to a lower mealiness is confirmed by the correlation analysis (r = 0.24). The sensory panel rated tubers from infected potato crops as the most yellowness. The flesh is tinged with yellow to a greater or lesser extent due to the presence of carotenoids (Burton 1989). Carotenoids belong to a larger class of compounds called terpenes. Zacharius and Kalan (1984) demonstrated that fungal and bacterial infections (*Erwinia carotovora* ssp. *atroseptica*, *Phytophthora infestans*) lead to an increase of the potato stress metabolite solavetivone, a sesquiterpene. Desjardins et al. (1995) found higher levels of sesquiterpenes, a subform of terpenes, in raw potatoes after tuber damage or microbial attack. The infestation of the tubers resulted in an increase of carotenoids and so in yellowness. Tubers with the highest yellow intensity were also characterized by highest bitter notes. The stress compound terpene is also responsible for vegetable bitterness up to pungency (Drewnowski and Gomez-Carneros 2000).

Storage is known to have an appreciable impact on undesirable reducing sugar accumulation in processing potatoes (Schuhmann, 1999; Kumar et al. 2004). This was confirmed in the present thesis in chapter 3. In the first trial year an increase of about 100 % was seen, and in the subsequent year, the year with appreciable higher sugar concentrations due to the early infestation with *P. infestans*, a more than 600 % increase was measured. The results support the investigations of Putz and Lindhauer (1994), who showed that immature tubers resulted in an increase in reducing sugar values by over 400 % in the first four weeks of storage. Throughout the experiments, data confirmed previous research which gave evidence that the individual growing season has a tremendous impact on the initial level as well as the accumulation of reducing sugars during storage (Kolbe 1990, Putz and Lindhauer 1994).

The results of this thesis show that the prevailing weather conditions, especially the length of growth period, had a main influence on yield and quality formation of tubers. Weather and climate are not under the control of the potato grower. Stress resulting from weather and climate is not under the control of the potato grower. However, through proper management, the damage to yield and tuber quality caused by environmental factors can be minimized. An adequate nutrient supply and an additional irrigation on sandy soils may contribute to safeguarding the yield and quality attributes. The choice of cultivar is an important measure, too. The knowledge about specific morphological features of different potato cultivars is helpful in the choice of cultivar adapted to the specific site conditions.

Due to the occurrence of *Phytophthora infestans* in both field studies, which possibly compensated the influence of agronomic measures on the sensory quality of organic potatoes, follow-up investigations on these measures should be definitely conducted, to further improve the quality of organic potatoes and thus meet the consumers’ market demands.

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Erklärung

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

Kassel, den 19.02.2013

Jana Franziska Dresow