Nutrient induced competition – use of concentrated nutrient solution for weed regulation

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Abstract

Weed reduction measures are an important tool in farming to avoid problems caused by weeds, firstly the competition between weed and crop plants for water and nutrients, and subsequently during mechanical harvesting. These days, application of herbicides is the most commonly used strategy to suppress weeds. The prohibition of herbicide application in organic farming and the possibility of using raw salts such as Kainit as a potassium source according to the EC Council Regulations No 834/2007 and No 889/2008 led to pot experiments to test the weed suppression effects of Kainit and ammonium sulphate solutions. Saturated and 1:1 diluted salt solutions were applied to the following weeds: *Galium aparine*, *Matricaria chamomilla*, *Thlaspi arvense* (in 2008); *Galium aparine*, *Matricaria chamomilla*, *Galinsoga parviflora* (in 2009). Most of the tested weed species showed a severe reduction in plant and root biomass after six and twenty-six days. The levels of applied nutrients in both plant and root increased during this period. The total applied nutrients by Nutrient Induced Competition (NIC) would not exceed the fertilizer recommendation amounts which would permit a field application. Further tests are necessary to evaluate the effects on other weed species, solutions of different concentrations, and possible harmful effects in case of unintentional NIC applications on arable crops.

Keywords: *nutrient Induced Competition, NIC, weed, nutrient solution*

Zusammenfassung

Nutrient induced competition – Einsatzmöglichkeiten konzentrierter Nährstofflösungen zur Unkrautregulierung

Unkräuter konkurrieren mit Feldfrüchten um Nährstoffe und Wasser und können maschinelle Ernteprozesse wesentlich behindern. Der Einsatz von Herbiziden ist heute die gängigste Praxis zur Unkrautkontrolle auf konventionell bewirtschafteten Ackerflächen. Im organischen Landbau ist der Einsatz von Herbiziden verboten, allerdings erlauben die EG-Verordnungen Nr. 834/2007 und 889/2008 die Ausbringung von Rohsalzen wie z. B. von Kainit als Kalium-Düngemittel. In einem Gefäßversuch sollte geprüft werden, ob stark konzentrierte Salzlösungen geeignet sind, das Wachstum von Unkräutern zu reduzieren. Gesättigte und 1:1 verdünnte Kainit- und Ammoniumsulfat-Lösungen wurden bei folgenden Unkräutern angewendet: *Galium aparine*, *Matricaria chamomilla*, *Thlaspi arvense* (im Jahr 2008); *Galium aparine*, *Matricaria chamomilla*, *Galinsoga parviflora* (im Jahr 2009). Die meisten der geprüften Unkräuter wiesen sechs und 26 Tage nach Ausbringung der Lösungen ein stark reduziertes Wachstum der Pflanzen und Wurzeln auf. Die Nährstoffgehalte in Pflanzen und Wurzeln erhöhten sich entsprechend der angewendeten Nährstofflösung. Mit dem Verfahren des ‚Nutrient Induced Competition' (NIC) ausgebrachte Nährstoffmengen überschreiten nicht die Werte der Düngeempfehlung, so dass die Anwendung im Feld möglich ist. Vor der Anwendung des NIC Verfahrens im Feld sollte die Wirkung der Salzlösung auf andere Unkräuter, die minimal notwendige Lösungskonzentration und die Auswirkung auf Feldfrüchte bei versehentlicher Anwendung geprüft werden.

Schlüsselwörter: *Nutrient Induced Competition, NIC, Unkraut, Nährstofflösung*

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1 Introduction

Commonly, inconvenient and undesirable plants in agricultural production are named weeds. Most of the so called weeds are not native, but were unintentionally introduced into Germany together with crop seeds from foreign areas such as the Mediterranean countries and continents such as North and South America. Weeds can have important economic impacts on agriculture. Firstly weeds are competitors for crop plants in terms of nutrients, water and light (Zwerger & Ammon, 2002; Lehoczky et al., 2006a; Lindquist et al., 2007; Wágner & Nádasy, 2007). Secondly weeds can significantly hamper mechanical harvest processes. Because of the ability of weed seeds to survive for years in agricultural soils before germination, farmers put great effort into minimising weed occurrence on their agricultural fields to keep crop yields high and preserve the value of the production area. Since the beginning of agricultural production farmers have tried to avoid the competition between cultivated and weed plant by the elimination of weeds; first manually and later on, after the introduction of row crops, by pulled mechanical hoes. The first herbicides were used at the end of the 19th century, but not until 60 years later were herbicides widely used. In the last 60 years the level of herbicide use has increased rapidly and dominates weed control practices today (Börner, 1995). Nevertheless, because of acknowledged problems caused by herbicides such as water pollution (e. g. Rasmussen et al., 2011) and weed resistance (e. g. Strek et al., 2012) as well as other, as yet unknown risks, alternative weed control systems have been attracting more interest in recent years. An important aspect of this development is the increasing interest in organically grown food or at least in the production of safe food particularly with regard to human health and environmental protection. Bond and Grundy (2001) provide an overview about non chemical weed management in organic farming systems.

Even though organic management practices try to close the nutrient cycle on the farm, nutrient exports through the sale of farm products and some nutrient losses through leaching are unavoidable. Such nutrient gaps cannot always be closed by on-farm produced organic fertilizers. Therefore, some mineral fertilization with raw salts e. g. Kainit is allowed according to the EC Council Regulations No 834/2007 and No 889/2008.

Haneklaus and Schnug (2006) introduced the term Nutrient Induced Competition (NIC) to describe the idea of applying strongly concentrated nutrient solutions specifically to weeds with the aim of causing physiological disorders and thus killing or at least reducing the weed vigour. Börner (1995) summarises the historical development of weed management practices mentioning the first experiments with $CuSO_4$ and Kainit. Besides the small selectivity of $CuSO_4$, the high application rates in particular cause problems in terms of copper accumulation in soils. Kainit is a raw mineral salt consisting of potassium chloride and magnesium sulphate mainly used as fertilizer. In early experiments with Kainit noticeable herbicide effects could be observed (Stender, 1902; Rademacher & Flock, 1952; Amann, 1956). Lately, the herbicide effects of Kainit have sparked new interest. Lukashyk et al. (2008) report results of greenhouse as well as field trials with Kainit dust and Kainit solution for controlling *Vicia hirsuta*. They conclude that the effect of Kainit to regulate weeds was highly dependent on weather conditions; especially in field trials temperature, humidity and precipitation affected the Kainit impact.

Weed occurrence can vary spatially and temporally (Gerhards, 2010). The improvements in Precision Agriculture (PA) tools to identify weed plants on the go by optical sensors accompanied by real-time spraying modules (Wang et al., 2007) would allow targeted placement not only of herbicides but also of nutrient solutions. It is widely accepted that the amount and timing of nitrogen fertilization can impact on the competition between cultivated and weed plants (Pulcher-Häussling, 1989; Lindquist et al., 2007). Some weed species benefit from nitrogen fertilization whereas others are either indifferent or suppressed by it. Bàrberi (2002) describes that faster nutrient release is often advantageous to weeds and that crop:weed competition as well as weed community dynamics may be altered by fertilization management. According to Bàrberi (2002) integrated cropping systems require appropriate timing of N mineral fertilization as a means to unbalance nutrient competition between crop and weeds to the benefit of the former. Tilman et al. (1999) describe an experiment to suppress dandelions by nutrient competition. In this case potassium fertilization and liming did increase the abundance of dandelions and the authors suggest a limitation of such fertilizers to decrease the occurrence of this weed. Combining such knowledge with PA technologies could allow the precise placement of fertilizers to influence the competition between cultivated and weed plants.

In this paper the results of greenhouse experiments to test the effect of a variety of highly concentrated nutrient solutions on the biomass production of different weed species are presented. In a preliminary experiment the weed suppressive effect of four nutrient solutions (Kainit, KCl, $(NH_4)_2SO_4$ and $CuSO_4$) were tested, followed by experiments focusing on the application of Kainit and $(NH_4)_2SO_4$ solutions in two different concentrations.

2 Materials and Methods

2.1 Experimental design

In June 2002, a preliminary greenhouse experiment was set up using two-leaf stage seedlings collected in nearby agricultural fields. Five annual and biannual weed species (*Chenopodium album* L., *Matricaria chamomilla* L., *Solanum nigrum* L., *Stellaria media* (L.) VILL., *Galinsoga parviflora* CAVAN.) were chosen. Seven seedlings were planted into Mitscherlich pots filled with a mixture of 4 kg agricultural soil (Luvisol) plus 2 kg sand. Altogether 80 pots were prepared, four repetitions for each weed species (5) and used nutrient solution (4). Under greenhouse conditions all weed species developed well.

Nineteen days after planting, during inflorescence emergence, nearly saturated Kainit, KCl, $(NH_4)_2SO_4$ and $CuSO_4$ solutions (subsequently referred to as saturated solution) were applied to induce nutrient stress. At three repetitions of each weed/solution combination 10 ml per pot of the appropriate solution were nebulised by a sprayer above the seven weed plants separating the pot from the surrounding replicates. A phosphorus-free detergent was used as surface-active agent. One pot of each treatment was kept as a control, the weed plants remained untreated. The weed development was visually observed and recorded for the following six weeks after inducing nutrient stress.

In 2008 and 2009 follow up experiments were set up with three annual weed species (2008: *Galium aparine* L., *Matricaria chamomilla* L., *Thlaspi arvense* L.; 2009: *Galium aparine* L., *Matricaria chamomilla* L., *Galinsoga parviflora* Cav.). Saturated as well as 1:1 diluted Kainit and $(NH_4)_2SO_4$ solutions were tested over two different durations (six and twenty-six days after application). Treatments were performed in four replications. In 2008, Kick/Brauckmann pots were filled with 9.0 kg fresh soil (Luvisol) from an organically managed field; the required two-leaf weed seedlings were collected from a nearby field and seven seedlings transferred into each of the prepared pots. In 2009, Kick/Brauckmann pots were filled with a mixture of 4.5 kg of the same soil used the year before, but mixed with 4.5 kg of sand. This time, the weeds were seeded into the pots and singled to seven plants per pot after germination (seven to sixteen days). Nutrient solutions were applied during inflorescence emergence in the same amounts used in 2008.

Table 1

Nutrient amounts per pot and per hectare added by salt solution application for Nutrient Induced Competition (NIC), 2008 and 2009

Treatment	Nutrient application [mg pot^{-1}]					
	Cl^-	Na	K	Mg	S	N
Control	-	-	-	-	-	-
Saturated Kainit	1,134	902	433	46	57	-
1:1 diluted Kainit	567	451	217	23	29	-
Saturated $(NH_4)_2SO_4$	-	-	-	-	1,285	1,124
1:1 diluted $(NH_4)_2SO_4$	-	-	-	-	643	571
	[kg ha^{-1}]					
Control	-	-	-	-	-	-
Saturated Kainit	298	237	114	12	15	-
1:1 diluted Kainit	149	119	57	6	8	-
Saturated $(NH_4)_2SO_4$	-	-	-	-	338	295
1:1 diluted $(NH_4)_2SO_4$	-	-	-	-	169	148

For the preparation of the saturated Kainit and $(NH_4)_2SO_4$ solutions 750 g salt was dissolved in 1000 ml aqua dest.. Eight pots of each weed species were sprayed with 10 ml of the saturated Kainit and $(NH_4)_2SO_4$ solution, respectively. Another eight pots of each weed species were sprayed with 10 ml of 1:1 diluted solutions. The adhesion of the solutions was again promoted by adding phosphorus-free detergent. Table 1 shows the amounts of nutrients added per pot for each treatment as well as calculated values in kg per hectare to allow comparisons at the field scale. The sodium (Na), potassium (K), magnesium (Mg), and sulphur (S) content of the saturated Kainit solution was analysed by ICP-OES (Spectro Flame M120S, Kleve, Germany) and the chloride (Cl^-) content by ion chromatography (Metrohm IC 761 Compact, Herisau, Switzerland).

For each weed species twelve pots were kept as control to be sampled four each on the day of NIC application, to evaluate the starting situation, followed by harvesting six as well as twenty-six days later at the same time with the NIC pots.

2.2 Plant sample analyses

Biomass production of plants and roots was recorded as dry matter (DM) at each sample date in 2008 and 2009. Plants were washed in distilled water, dried in a ventilated oven at 55 °C and finely ground in a vibratory disc mill (Retsch RS1, Haan, Germany). Roots were acquired by emptying the Kick/Brauckmann pots and separating roots from soil. After thoroughly washing three times with distilled water, the same preparation process took place as that used for the plant samples. Total carbon (C) and nitrogen (N) contents of plants and roots were analysed by dry combustion (Elementar vario MAX CNS, Hanau, Germany). Major plant and root nutrients phosphorus (P), S, K, calcium (Ca), Mg and Na were determined after nitric acid microwave digestion (CEM MARS, Metthews, USA) by Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES, Spectro Flame M120S, Kleve, Germany).

2.3 Soil sample analyses

Soil analysis was conducted at the end of each partial experiment. The soil was air-dried and sieved to a particle size ≤ 2 mm.

Due to the use of different salt solutions, the chemical analyses of the soil samples from the first pot trial focused on K and copper (Cu) added by the NIC treatments. Plant available K was extracted by a calcium acetate lactate (CAL) according to Schüller (1969) and measured by flame photometer (Eppendorf, Elex 6361, Hamburg, Germany). The plant available Cu content was extracted by 0.43 M HNO_3 and determined by atomic absorption spectroscopy (Unicam 929 AA spectrometer, ATI Unicam, Cambridge, UK) according to Westerhoff (1954/1955).

Soil samples of 2008 and 2009 were analysed for soil electrical conductivity (EC) in a 1:5 soil:water extract, pH in a 1:5 soil: 0.01 M calcium chloride. Plant available P, K and Na was determined in a calcium acetate lactate (CAL) extract according to Schüller (1969), and plant available Mg content in a 0.025 N calcium chloride extract according to Schachtschabel (1954). The various nutrients were measured by ICP-OES (Spectro Flame M120S, Kleve, Germany).

2.4 Statistical analyses

To test for significant differences between treatments, analysis of variance (one-way ANOVA) and Tukey-Kramer *t*-tests were performed with JMP (Version 8, SAS Institute, Cary, USA). Treatment differences were considered significant at *P* values < 0.05.

3 Results and Discussion

The preliminary experiment in 2002 produced a reduction in weed growth in comparison to the control pot for all nutrient solutions and all weed species except for *Chenopodium album* L.. Six days after NIC application plants were greatly reduced in size and further plant growth was halted. Nevertheless, most weeds started to recover after two to three weeks. Hygroscopic effects could be observed especially on days with higher humidity and in early morning hours, rewetting the salt crusted weed leaves. For *Chenopodium album* L. only the application of $CuSO_4$ solution had a vigour and plant growth suppressing effect, which confirms the exceptional salt resistance of *Chenopodium* species (Reimann, 1992) which could be caused by the ability of some plants to adapt to soil salinity by selective absorption of osmotic effective ions (Rains, 1972). The copper load added by applying $CuSO_4$ solution resulted in a tenfold increase in copper concentration in the soil (data not shown) and would result in a load of 27 times more copper than is allowed by the EU regulations for organic agriculture annually. Further tests with much lower Cu concentrations and/or a reduction of the amount sprayed would be necessary to draw appropriate conclusions. General concerns with regard to soil contamination by Cu and the promising results of the other macro nutrient solutions led to the decision to abandon further tests at this stage.

Taking into account the results of the preliminary experiment the experimental design was modified. First of all the main interest was to test the effect of Kainit because of the potential usage in organic farming. Also of interest was whether other mineral nutrients used as fertilizers in conventional farming could be used to induce nutrient competition. Therefore in 2008 and 2009 only Kainit and $(NH_4)_2SO_4$ solutions were tested. The aim was also to test if lower concentration solutions would be able to achieve weed suppression. In a first step the nutrient concentration of the solution was diluted 1:1 with aqua dest. From the 2002 experiment it was known that some of the weeds started to recover two to three weeks after NIC application. This observation confirms the results of Meiri and Poljakoff-Mayber (1970) that the growth of bean plants abruptly exposed to salt stress recovered with time, but at a much lower rate than the control plants. Therefore, it was decided that treatment effects on biomass production should be tested two times during the experiment, about one and four weeks after NIC application. Table 2 shows the treatment effects on plant and root biomass production six days after NIC application.

Contrasting treatment effects could be observed six days after NIC application (Table 2). For all weed species and treatments a reduction in weed biomass was achieved compared to the control pots without NIC treatment. However, only certain treatments showed significant effects. The root development was also decreased by most treatments except in 2008, when the diluted Kainit solution seemed to have a fertilizing

Table 2

Analysis of variance (ANOVA)[1] and Tukey-Kramer *t*-test[2] on plant and root biomass production six days after application of nearly saturated and 1:1 diluted Kainit and $(NH_4)_2SO_4$ solutions on three weed species in 2008 and 2009

Year and plant part	Weed species	Dry matter [g pot^{-1}] before NIC appl.	six days after NIC application: Kainit		$(NH_4)_2SO_4$		control	ANOVA *p*-value[1]
			1:0	1:1	1:0	1:1		
2008 – shoots	*Galium aparine* L.	3.68	4.60	5.40	4.88	4.37	5.73	n.s. $_{0.3517}$
	Matricaria chamomilla L.	3.55	5.16^{ab}	4.58^{b}	4.67^{b}	4.83^{ab}	6.34^{a}	* $_{0.0202}$
	Thlaspi arvense L.	3.05	3.69	3.41	3.69	3.47	4.43	n.s. $_{0.5031}$
2008 – roots	*Galium aparine* L.	1.88	1.78^{ab}	2.84^{a}	1.80^{ab}	1.56^{b}	2.64^{ab}	* $_{0.0141}$
	Matricaria chamomilla L.	1.54	1.47^{ab}	1.39^{b}	1.25^{b}	1.64^{ab}	2.18^{a}	* $_{0.0107}$
	Thlaspi arvense L.	0.70	0.90^{ab}	0.77^{b}	0.82^{ab}	0.82^{ab}	1.09^{a}	* $_{0.0234}$
2009 – shoots	*Galinsoga parviflora* Cav.	4.79	5.49^{ab}	5.07^{ab}	5.02^{ab}	4.61^{b}	6.00^{a}	* $_{0.0161}$
	Galium aparine L.	5.19	6.00^{b}	5.67^{b}	5.90^{b}	5.99^{b}	7.69^{a}	** $_{0.0066}$
	Matricaria chamomilla L.	4.03	6.06	5.20	5.02	6.13	5.18	n.s. $_{0.1138}$
2009 – roots	*Galinsoga parviflora* Cav.	1.85	2.01^{ab}	1.75^{b}	1.74^{b}	1.74^{b}	2.45^{a}	* $_{0.0186}$
	Galium aparine L..	1.48	1.65^{b}	1.85^{b}	1.56^{b}	1.71^{b}	2.46^{a}	** $_{0.0020}$
	Matricaria chamomilla L.	1.12	1.83	1.91	1.61	1.90	1.90	n.s. $_{0.5127}$

[1] Significance of p-levels: n.s. = not significant (p > 0.05), * = 5 % (p ≤ 0.05), ** = 1 % (p ≤ 0.01), *** = 0.1 % (p ≤ 0.001).

[2] Levels not connected by the same letter are significantly different at the 5 % level (Tukey-Kramer *t*-test)

Table 3

Analysis of variance (ANOVA)[1] and Tukey-Kramer *t*-test[2] on plant and root biomass production twenty-six days after application of nearly saturated and 1:1 diluted Kainit and $(NH_4)_2SO_4$ solutions on three weed species in 2008 and 2009

Year and plant part	Weed species	before NIC appl.	Dry matter [g pot⁻¹] twenty-six days after NIC application: Kainit 1:0	Kainit 1:1	$(NH_4)_2SO_4$ 1:0	$(NH_4)_2SO_4$ 1:1	control	ANOVA *p*-value[1]
2008 – shoots	*Galium aparine* L.	3.68	6.83	7.40	7.32	7.38	8.29	n.s. 0.6964
	Matricaria chamomilla L.	3.55	6.41[b]	6.59[b]	10.22[a]	7.99[b]	7.66[b]	*** 0.0005
	Thlaspi arvense L.	3.05	3.89[b]	3.52[b]	4.02[b]	3.71[b]	6.11[a]	*** <0.0001
2008 – roots	*Galium aparine* L.	1.88	2.11[bc]	2.74[ab]	1.30[c]	1.63[bc]	3.55[a]	*** <0.0001
	Matricaria chamomilla L.	1.54	1.20[b]	1.43[ab]	1.71[ab]	1.48[ab]	2.13[a]	* 0.0492
	Thlaspi arvense L.	0.70	0.66[b]	0.60[b]	0.61[b]	0.60[b]	1.00[a]	*** 0.0009
2009 – shoots	*Galinsoga parviflora* Cav.	4.79	5.28[b]	6.44[b]	5.11[b]	6.18[b]	12.67[a]	*** <0.0001
	Galium aparine L.	5.19	5.85[b]	6.74[b]	7.08[b]	6.42[b]	8.79[a]	*** 0.0006
	Matricaria chamomilla L.	4.03	6.97[b]	7.53[b]	6.45[b]	6.93[b]	10.05[a]	*** <0.0001
2009 – roots	*Galinsoga parviflora* Cav.	1.85	1.70[bc]	1.91[b]	1.19[d]	1.52[cd]	4.84[a]	*** <0.0001
	Galium aparine L..	1.48	2.04[bc]	2.61[b]	1.49[c]	1.67[bc]	3.93[a]	*** <0.0001
	Matricaria chamomilla L.	1.12	1.64[b]	1.84[b]	1.46[b]	1.61[b]	2.60[a]	*** <0.0001

[1] Significance of p-levels: n.s. = not significant (p > 0.05), * = 5 % (p ≤ 0.05), ** = 1 % (p ≤ 0.01), *** = 0.1 % (p ≤ 0.001).
[2] Levels not connected by the same letter are significantly different at the 5 % level (Tukey-Kramer *t*-test)

effect on *Galium aparine* L.. This result could not be reproduced in 2009.

Twenty-six days after NIC application biomass of all weed species was significantly reduced by all four nutrient solutions, except for *Galium aparine* L. in 2008 (Table 3). Anyhow, comparisons to the biomass measured before the NIC application show that the plant biomass increased. Root biomass was in some cases reduced below the level when treatments were applied (Table 3). The highest reduction in plant biomass of 60 % was recorded for *Galinsoga parviflora* Cav. twenty-six days after NIC with saturated $(NH_4)_2SO_4$ solution in 2009. The same treatment also showed a root biomass reduction of 75 %.

Even though significant weed biomass reduction could be achieved by NIC application, it can be questioned if an earlier application at the two to four leave stage of the seedlings would have resulted in a better weed suppression. Lukashyk et al. (2008) observed that the effect of Kainit applications to suppress *Vicia hirsuta* was less successful at a later date. The best effects were recorded on *Vicia hirsuta* at juvenile stage. As with most conventional herbicides it can be expected that the efficiency of weed reduction could be im-proved by an earlier application. In 2008, the decision to apply the nutrients in the presented experiment during inflorescence emergence was made to avoid any eventual influences from planting the weeds into the pots. In 2009 the NIC treatment was conducted at the same growth stage as in the year before to allow comparisons between experimental years. A field experiment with naturally emerging weeds would be preferred to test NIC application at an earlier growth stage.

At inflorescence emergence, the plants covered in the majority of pots most of the soil. But, the canopy closure varied between the weed species depending on the leaf structure. Therefore, it was unavoidable that during the application some of the NIC solutions were also sprayed onto the soils of the pots. Nutrients sprayed onto the soil were washed directly into the soil with irrigation water, which was carefully placed below the canopy. Additionally, rewetting of the salt crusted leaves added nutrient to the soil, especially after the wilting process of the plants left salt crusted leaf tissues covering the soil. Such transfer of salts would also occur in the field as an inevitable consequence of rainfall. No differentiation can be made between effects resulting from osmotic stress of plant tissues and salinity of the soil.

Most NIC applications resulted in increasing uptake of supplied nutrients confirming the observations of Lehoczky et al. (2006b). Figure 1 shows clearly the variation between treatments in plant and root nutrient concentrations of *Galium aparine* L. and *Galinsoga parviflora* Cav. twenty-six days after NIC application in 2009.

The nutrient increase in the roots is an indicator that a nutrient transfer took place from the soil into the plants. The application of concentrated nutrient solutions to the soil did increase soil EC up to 6-fold for some treatments (e. g. *Matricaria chamomilla* L. 2008, $(NH_4)_2SO_4$ 1:0 solution) whilst EC for most treatments did increase 1-2-fold (Table 4). Table 4 also shows that the application of saturated Kainit solutions led to an increase in soil content of K for most weeds six and twenty-six days after application. But the crop plant uptake during the growing season needs to be taken into account.

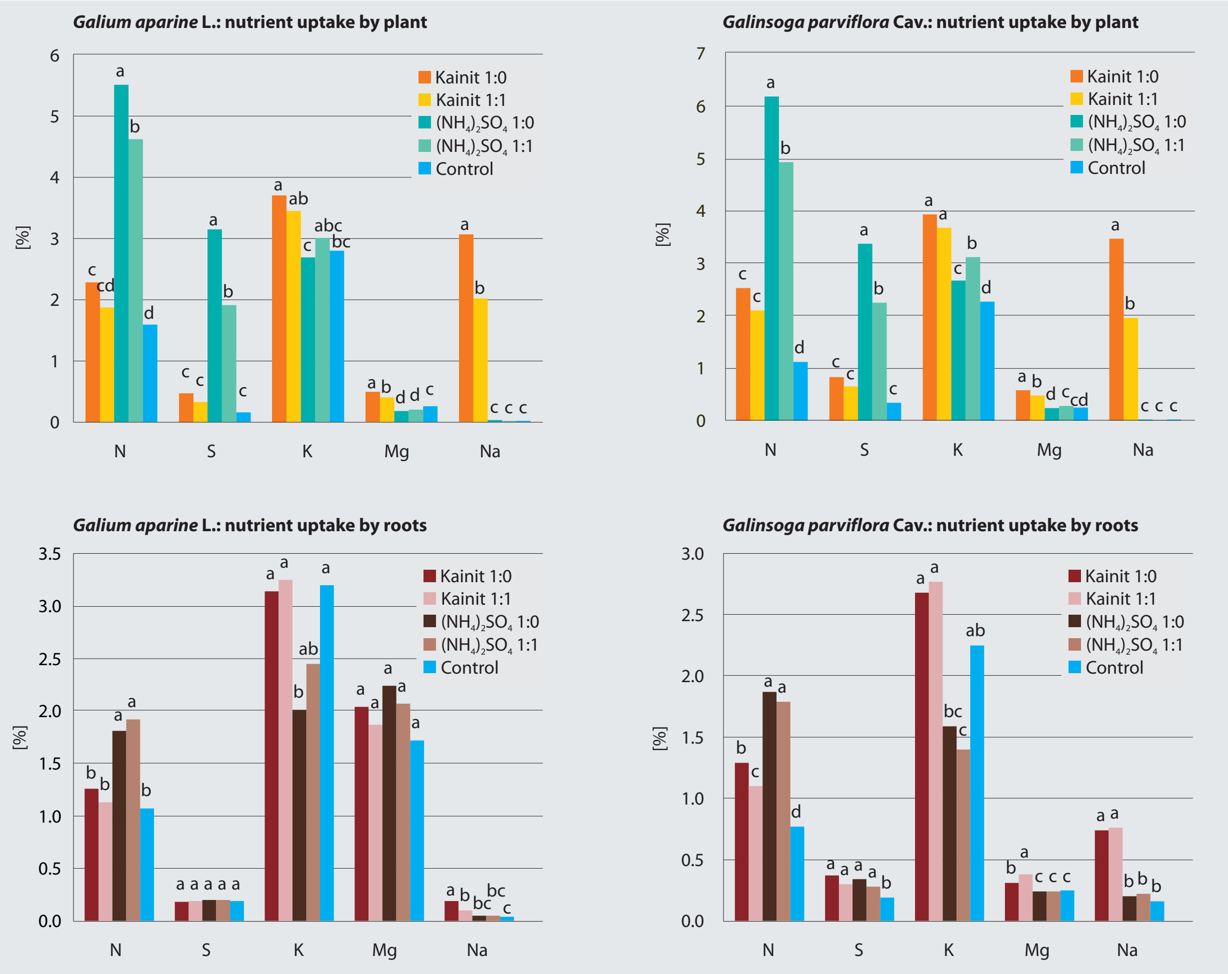

Figure 1

Nutrient uptake by plants and roots of *Galium aparin* L. and *Galinsoga parviflora* Cav., twenty-six days after NIC application (2009). Levels not connected by the same letter are significantly different at the 5 % level (Tukey-Kramer *t*-test).

Nevertheless, the results are not universal and show that the amount of K applied to the soil (Table 1) even with the saturated solution is around or below the usual application rate in conventional farming, depending on the crop grown.

Considering that for example maize has an average nutrient uptake of 152 kg ha^{-1} N and K, 26 kg ha^{-1} Mg and 17 kg ha^{-1} S per vegetation period it can be seen, that the nutrient amounts supplied with the saturated $(NH_4)_2SO_4$ solution (Table 1) would increase the risk of nitrogen leaching into ground and surface waters. The diluted solutions also had a weed suppressing effect in most cases. If weed control could be achieved by application of less concentrated $(NH_4)_2SO_4$ solution too, the risk of nitrogen leaching would decrease. More research is needed to establish the lowest concentration possible to achieve a reduction in weed growth. The results of the presented experiments show already that this lowest concentration will vary between weed species and that some weed species cannot be controlled by NIC. This confirms observations of Grant et al. (2006) who reported that crop biomass yield (canola and wheat) did not increase with K fertilization but some weed species biomass increased as such providing a competitive advantage for these weed species over the agricultural crop. Generally it needs to be kept in mind that the applied nutrients are included into the nutrient balance of the field and that further fertilization will be adjusted. If the NIC application takes place using automated weed detection by spectral reflectance, it is important to spatially record the application amounts and counterbalance the nutrients also by spatial fertilization. Notwithstanding that such techniques are still hampered by some limitations which need to be overcome before a wider use can be expected (Christensen et al., 2009), uniform NIC applications in a rate below or around the amount derived from fertilizer recommendations can take place. If a spatial application is planned, the actual K content of the soil and expert knowledge about the major weed species in the field and their behaviour in response to nutrients needs to be considered. At the moment NIC applications can only take place before crop plant emergence or in row crops with wide row widths such as maize plants. Field experiments would be useful to evaluate such applications in agricultural ecosystems as it is known that the efficiency of chemical substances can vary depending on weather and soil conditions (Schlosser, 1987; Kelly & Harwell, 1989).

Table 4

Analysis of variance (ANOVA)[1] and Tukey-Kramer *t*-test[2] on soil EC, K and Na content six and twenty-six days after application of nearly saturated and 1:1 diluted Kainit and $(NH_4)_2SO_4$ solutions on three weed species in 2008 and 2009

Soil variable	Weed species	before NIC appl.	Treatment: Kainit 1:0	Kainit 1:1	$(NH_4)_2SO_4$ 1:0	$(NH_4)_2SO_4$ 1:1	control	ANOVA *p*-value[1]
EC [µs cm^{-1}] 2008 6 daNIC[#]	*Galium aparine* L.	89	116^{b}	129^{b}	300^{a}	92^{b}	94^{b}	*** $_{<0.0001}$
	Matricaria chamomilla L.	92	201^{bc}	151^{c}	594^{a}	372^{b}	94^{c}	*** $_{<0.0001}$
	Thlaspi arvense L..	102	292^{abc}	123^{bc}	406^{a}	344^{ab}	100^{c}	** $_{0.0043}$
EC [µs cm^{-1}] 2008 26 daNIC[#]	*Galium aparine* L.	89	85	83	89	88	82	n.s. $_{0.2466}$
	Matricaria chamomilla L..	92	107	89	100	88	84	n.s. $_{0.5632}$
	Thlaspi arvense L.	102	98^{a}	89^{ab}	91^{ab}	93^{ab}	82^{b}	** $_{0.0089}$
EC [µs cm^{-1}] 2009 6 daNIC[#]	*Galinsoga parviflora* Cav.	72	117^{b}	86^{c}	150^{a}	108^{b}	58^{d}	*** $_{<0.0001}$
	Galium aparine L.	63	117^{ab}	89^{cd}	141^{a}	108^{bc}	63^{d}	*** $_{<0.0001}$
	Matricaria chamomilla L.	77	135^{b}	99^{b}	240^{a}	129^{b}	68^{b}	*** $_{0.0010}$
EC [µs cm^{-1}] 2009 26 daNIC[#]	*Galinsoga parviflora* Cav.	72	135^{b}	108^{b}	214^{a}	122^{b}	54^{c}	*** $_{<0.0001}$
	Galium aparine L.	63	147^{ab}	96^{bc}	172^{a}	130^{ab}	63^{c}	*** $_{0.0004}$
	Matricaria chamomilla L.	77	157^{b}	112^{bc}	242^{a}	142^{b}	60^{c}	*** $_{<0.0001}$
K [mg kg^{-1}] 2008 6 daNIC[#]	*Galium aparine* L.	156	156^{ab}	148^{ab}	147^{b}	162^{a}	158^{ab}	* $_{0.0184}$
	Matricaria chamomilla L.	153	160^{a}	158^{a}	154^{ab}	143^{b}	143^{b}	** $_{0.0041}$
	Thlaspi arvense L.	158	195^{a}	151^{b}	153^{b}	149^{b}	157^{b}	*** $_{<0.0001}$
K [mg kg^{-1}] 2008 26 daNIC[#]	*Galium aparine* L.	156	156^{a}	155^{a}	143^{b}	149^{ab}	145^{ab}	** $_{0.0082}$
	Matricaria chamomilla L.	153	160^{a}	157^{a}	138^{b}	137^{b}	133^{b}	*** $_{0.0001}$
	Thlaspi arvense L.	158	151	141	141	144	148	n.s. $_{0.2721}$
K [mg kg^{-1}] 2008 6 daNIC[#]	*Galinsoga parviflora* Cav.	77	78^{a}	69^{bc}	68^{cd}	75^{ab}	61^{d}	*** $_{<0.0001}$
	Galium aparine L.	70	73	69	73	73	65	n.s. $_{0.1179}$
	Matricaria chamomilla L.	80	87^{a}	77^{b}	75^{b}	71^{b}	74^{b}	*** $_{<0.0001}$
K [mg kg^{-1}] 2009 26 daNIC[#]	*Galinsoga parviflora* Cav.	77	81^{a}	72^{a}	72^{a}	71^{a}	56^{b}	** $_{0.0012}$
	Galium aparine L.	70	92^{a}	75^{b}	72^{bc}	74^{b}	63^{c}	*** $_{<0.0001}$
	Matricaria chamomilla L.	80	94^{a}	88^{ab}	81^{abc}	73^{c}	75^{bc}	** $_{0.0020}$
Na [mg kg^{-1}] 2008 6 daNIC[#]	*Galium aparine* L.	54	74^{a}	68^{ab}	44^{bc}	43^{c}	53^{abc}	** $_{0.0035}$
	Matricaria chamomilla L.	52	124^{a}	78^{ab}	53^{b}	56^{b}	48^{b}	** $_{0.0054}$
	Thlaspi arvense L.	48	187^{a}	67^{b}	44^{b}	49^{b}	48^{b}	*** $_{<0.0001}$
Na [mg kg^{-1}] 2008 26 daNIC[#]	*Galium aparine* L.	54	44^{ab}	44^{ab}	41^{b}	40^{b}	53^{a}	* $_{0.0127}$
	Matricaria chamomilla L.	52	62	52	59	52	48	n.s. $_{0.3330}$
	Thlaspi arvense L.	48	56^{a}	44^{b}	45^{b}	44^{b}	41^{b}	** $_{0.0014}$
Na [mg kg^{-1}] 2009 6 daNIC[#]	*Galinsoga parviflora* Cav.	31	79^{a}	53^{b}	32^{d}	44^{c}	34^{d}	*** $_{<0.0001}$
	Galium aparine L.	42	78^{a}	59^{b}	33^{c}	35^{c}	39^{c}	*** $_{<0.0001}$
	Matricaria chamomilla L.	37	87^{a}	60^{b}	36^{c}	38^{c}	37^{c}	*** $_{<0.0001}$
Na [mg kg^{-1}] 2009 26 daNIC[#]	*Galinsoga parviflora* Cav.	31	97^{a}	70^{ab}	35^{c}	43^{bc}	30^{c}	*** $_{<0.0001}$
	Galium aparine L.	42	106^{a}	68^{b}	32^{c}	34^{c}	39^{c}	*** $_{<0.0001}$
	Matricaria chamomilla L.	37	102^{a}	74^{b}	40^{c}	38c	36^{c}	*** $_{<0.0001}$

[1] Significance of p-levels: n.s. = not significant ($p > 0.05$), * = 5 % ($p \leq 0.05$), ** = 1 % ($p \leq 0.01$), *** = 0.1 % ($p \leq 0.001$).

[2] Levels not connected by the same letter are significantly different at the 5 % level (Tukey-Kramer *t*-test).

[#] daNIC stands for 'days after NIC' application

4 Conclusions

The presented results demonstrate the potential of NIC applications with Kainit and $(NH_4)_2SO_4$ solutions to suppress weeds. But it was also found that *Chenopodium album* L. was not affected. Further research is necessary to evaluate which weed species are susceptible to NIC applications and to test the minimum concentrations that are effective. It would also be useful to test the resistance of crop plants to unintentionally applied nutrient solutions. In cases where crop plants show resistance to the nutrient solutions or where the solutions can be placed precisely on top of the weeds, for example with robots, it would be possible to carry out NIC applications during the plant growth period.

References

Amann F (1956) Untersuchungen über die Bekämpfung des Franzosenkrautes (Galinsoga parviflora Cavanilles) in Hackfrucht- und Gemüse-Kulturen, insbesondere mit Kalkstickstoff und Hederich-Kainit. Hohenheim : Univ, 90 p

Bàrberi P (2002) Weed management in organic agriculture : are we addressing the right issues? Weed Res 42(3):177-193

Börner H (1995) Unkrautbekämpfung. Jena : Fischer, 315 p

Bond W, Grundy AC (2001) Non-chemical weed management in organic farming systems. Weed Res 41:383-405

Christensen S, Søgaard HT, Kudsk P, Nørremark M, Lund I, Nadimi ES, Jørgensen R (2009) Site-specific weed control technologies. Weed Res 49(3):233-241

Gerhards R (2010) Spatial and temporal dynamics of weed populations. In: Oerke E-C (ed) Precision crop protection : the challenge and use of heterogeneity. Dordrecht : Springer, pp 17-25

Grant CA, Derksen DA, Blackshaw RE, Entz T, Janzen HH (2006) Differential response of weed and crop species to potassium and sulphur fertilizers. Can J Plant Sci 87(2):293-296

Haneklaus S, Schnug E (2006) Site-specific nutrient management : objectives, current status and future research needs. In: Srinivasan A (ed) Handbook of precision agriculture : principles and applications. New York : Food Products Pr, pp 91-151

Kelly JR, Harwell MA (1989) Indicators of ecosystem response and recovery. In: Levin SA, Harwell MA, Kelly JR, Kimball KD (eds) Ecotoxicology : problems and approaches. New York : Springer, pp 9-35

Lehoczky E, Németh T, Reisinger, P, Radimszky L, Kömíves T (2006a) Effect of weediness on the water content oft he soil : a field study. Commun Soil Sci Plant Anal 37:2673-2678

Lehoczky E, Tóth Z, Kismányoky A, Kismányoky T (2006b) Nutrient uptake by weeds in a long-term maize field experiment. Agrokemia és Talajtan 55:175-182

Lindquist JL, Barker DC, Knezevic SZ, Martin AR, Walters DT (2007) Comparative nitrogen uptake and distribution in corn and velvetleaf (Abutilon theophrasti). Weed Sci 55:102-110

Lukashyk P, Berg M, Köpke U (2008) Nutzung von Kainit zur Regulierung von Vicia hirsute (L.) S.F.Gray im Ökologischen Landbau. J Plant Diseases Protect Spec Iss 21:419-424

Meiri A, Poljakoff-Mayber A (1970) Effect of various salinity regimes on growth, leaf expansion and transpiration rate of bean plants. Soil Sci 109:26-34

Pulcher-Häussling M (1989) Einfluss der N-Düngung auf die Konkurrenz zwischen Unkraut und Getreide und den Abbau von Unkrautsamen im Boden. Hohenheim : Univ, 120 p

Rademacher B, Flock A (1952) Untersuchungen über die Anwendung von Kalkstickstoff und Feinkainit gegen die Ackerunkräuter der Lehm- und Sandböden. Z Acker- Pflanzenbau 94:1-54

Rains DW (1972) Salt transport by plants in relation to salinity. Ann Rev Plant Physiol 23:367-388

Rasmussen JJ, Baattrup-Pedersen A, Wiberg-Larsen P, McKnight US, Kronvang B (2011) Buffer strip width and agricultural pesticide contamination in Danish lowland streams : implications for stream and riparian management. Ecol Engineering 37(12):1990-1997

Reimann C (1992) Sodium exclusion by *Chenopodium* Species. J Exp Bot 43(249):503-510

Schachtschabel P (1954) Das pflanzenverfügbare Magnesium im Boden und seine Bestimmung. Z Pflanzenernähr Düng Bodenkd 67:9-23

Schlosser HJ (1987) Bewertungsprobleme bei der Bearbeitung der „Literaturstudie über Kriterien für ökotoxikologische Untersuchungen der Belastung von Ökosystemen". Mitt Biol Bundesanst Land-Forstwirtsch 234:6-15

Schüller H (1969) Die CAL-Methode, eine neue Methode zur Bestimmung des pflanzenverfügbaren Phosphats in Böden. Z Pflanzenernähr Bodenkd 123:48-63

Stender A (1902) Untersuchungen über die Unkrautverteilung durch Düngesalze. Rostock . Univ, 68 p

Strek HJ, Hess M, Kaiser J (2012) Glyphosat-Resistenz in amerikanischen Reihenkulturen und Lehren für die Unkrautbekämpfung in Europa. Julius-Kühn-Archiv 434(1):171-176

Tilman EA, Tilman D, Crawley MJ, Johnston AE (1999) Biological weed control via nutrient competition : potassium limitation of dandelions. Ecol Appl 9(1):103-111

Wágner G, Nádasy E (2007) Competition for nutrients between weeds and green pea. Cereal Res Commun 35(2):1325-1328

Wang N, Zhang N, Wie J, Stoll Q, Peterson DE (2007) A real-time, embedded, weed-detection system for use in wheat fields. Biosyst Engineering 98:276-285

Westerhoff H (1954/55) Beitrag zur Kupferbestimmung im Boden. Landwirtsch Forsch 7:190-193

Zwerger P, Ammon HU (2002) Unkraut : Ökologie und Bekämpfung. Stuttgart : Ulmer, 419 p