Suitability of soil electrical conductivity as an indicator of soil nitrate status in relation to vegetable cultivation practices in the Yangtze River Delta of China

Yi-Chao Shi*, **, Zheng-Yi Hu*, ** Silvia Haneklaus***, Wei-Guo Long**, ****, Xu Xia**, Yan-Wen Zhao****, Tian Lin** and Ewald Schnug***

Abstract

In soil samples from sites where vegetables were grown in foil tunnels and open fields. Chemical soil analysis comprised the parameters electrical conductivity (EC), pH, NO_3-N, NH_4-N, total N and organic matter. Cultivation practices had no influence on soil pH values. In comparison, EC was significantly higher with 462.5 µS/cm in soils under foil tunnels than in open fields with a mean value of 251.2 µS/cm. About one third (35 %) of all samples showed secondary salinization with EC values > 500 µS/cm under foil tunnels, and still 9 % of all samples from field-grown vegetables. Soil EC values increased with the time period of vegetable growing and exceeded 500 µS/cm after more than 4 years of continuous cultivation. A highly significant correlation $p < 0.001$) was determined between soil NO_3-N and soil EC irrespective of the cultivation practice if EC was < 500 µS/cm, while no relationship existed in soils with EC values > 500 µS/cm. The results suggest that NO_3-N is a main factor influencing EC values, but NO_3-N is of minor relevance for the complex phenomenon of secondary salinization as found in soils under foil tunnels. This implies that a reduction of the N fertilizer input is not sufficient to decrease EC values in these production units. Soil EC values might be used as an indicator for excessive NO_3-N soil contents and as a benchmark for calculating site-specific N rates. Thus crop productivity and quality parameters of vegetables can be improved and environmental burdens, for example N loads to water bodies significantly reduced.

Keywords: codes of good agricultural practice (GAP), eutrophication, foil tunnel, geo-electric sensor, site-specific nutrient management, secondary salinization

Zusammenfassung

Eignung der elektrischen Leitfähigkeit als Indikator für den Nitratgehalt im Boden in Gemüseanbaugebieten des Yangtze Flussdeltas in China

In Bodenproben von Feldern auf denen Gemüse im Freiland und unter Folientunneln angebaut wurde, wurden elektrische Leitfähigkeit (EC), pH, NO_3-N, NH_4-N, Gesamt-N und der Gehalt an organischer Substanz bestimmt. Das Anbauverfahren hatte keinen Einfluss auf den pH-Wert im Boden. Böden unter Folientunneln wiesen mit 462,5 µS/cm eine signifikant höhere elektrische Leitfähigkeit auf als Böden im Freiland (251,2 µS/cm). Ungefähr ein Drittel (35 %) aller Proben unter Folientunneln und 9 % im Freiland wiesen mit > 500 µS/cm eine sekundäre Versalzung auf. Bereits nach 4 Jahren kontinuierlichen Gemüseanbaus wurde der kritische Wert von 500 µS/cm überschritten. Es wurde eine hochsignifikante Korrelation ($p < 0{,}001$) zwischen NO_3-N und EC unabhängig vom Anbauverfahren ermittelt, sofern die EC-Werte < 500 µS/cm lagen. Bei höheren EC-Werten bestand hingegen keine signifikante Beziehung. Der NO_3-N Gehalt im Boden hatte einen starken Einfluss auf die elektrische Leitfähigkeit, während NO_3-N für das komplexe Phänomen der sekundären Versalzung nur eine untergeordnete Rolle spielt. Dies bedeutet, dass eine Reduzierung des N-Düngemitteleinsatzes in diesem Produktionssystem nicht ausreichend ist, um die EC-Werte zu senken. Die elektrische Leitfähigkeit könnte nicht nur als Indikator für exzessive NO_3-N Gehalte im Boden, sondern auch als Orientierungswert für standortspezifische N-Gaben dienen. Auf diese Weise ließen sich Ertrags- und Qualitätsparameter des Gemüses verbessern und die umweltbeeinträchtigende Wirkung durch den Austrag von N in Gewässer signifikant reduzieren.

Schlüsselworte: Eutrophierung, Folientunnel, geo-elektrischer Sensor, Regeln guter fachlicher Praxis, sekundäre Versalzung, teilfächenspezifische Düngung

* College of Resources and Environment, Graduate University of Chinese Academy of Sciences, 19A, Yuquan Road, Beijing, China, 100049

** State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, 71st East Beijing Road, Nanjing, P.R. China, 210008

*** Julius Kühn-Institut (JKI), Institute for Crop and Soil Science, Federal Research Centre for Cultivated Plants, Bundesallee 50, D-38116 Braunschweig, Germany

**** Nanjing Agricultural University, 1st Weigang Road, Nanjing, China, 210095

Introduction

In China, the cultivation area of vegetables increased from 9.5×10^6 ha (6.3 % of arable land) in 1995 to 1.8×10^7 ha (11.6 % of arable land) in 2006 (Anon, 2007). The Yangtze River Delta is meanwhile a major vegetable production centre in China. In 2007, 10.8 % of all vegetables originated from this area (Anon, 2007). Land use changed basically during the past years from paddy to vegetable fields, and from conventional field vegetable cultivation to foil tunnel systems. It was observed that crop productivity decreased distinctly over time (Wang, 2005; Du et al., 2006) and secondary salinization seems to be a major obstacle, particularly in foil tunnel systems because of an excessive use of nitrogen (N) fertilizers (Cao et al., 2004; Chen et al., 2004; Shi et al., 2008). Excessive fertilizer use in specialty crops is a well-known problem with serious agronomic and environmental implications. In case of N, NO_3-N will accumulate in soils and crops and NO_3-N may diminish crop quality if taken up in significant amounts. Ecological problems comprise gaseous N losses to the atmosphere, leaching of NO_3-N, eutrophication of water bodies and soil salinization, particularly when vegetable crops are grown under cover (Maxted and Diebel 2008; Stigter et al., 1998; Chen et al., 2004). Vegetable crops and particularly those grown under cover receive fertilizers more often and at higher rates than cereals and oilseed (Power and Schepers, 1989; Cao et al., 2004; He et al., 2007). In soils under foil tunnels NO_3 accounted for 56 to 76 % of all anions (Yu et al., 2005).

One factor influencing the salt content in the soil is the concentration of soluble nutrients and geo-electric sensor data have been used to delineate N management zones in Precision Agriculture (Cockx et al., 2004). Despite this basic knowledge, only limited studies have been carried out in vegetable farming to determine interactions between NO_3-N and electric conductivity (EC) in soils (Cao et al., 2004; Ju et al., 2007; Shi et al., 2008 and 2009). Soil EC values of > 500 µS/cm impaired crop growth and soil EC values of > 1000 µS/cm resulted in withering of the crop (Li, 1993). A soil EC value of > 500 µS/cm has been defined as the critical value for secondary salinization in foil tunnel production systems (Li, 1993). Surveys on fertilizer-related salinization in conventional field-grown vegetables are scarce. It was the objective of the presented study firstly to determine soil EC values and assess the risk of secondary salinization in relation to cultivation practices in vegetable growing in the Yangtze River Delta of China, and secondly to evaluate the suitability of EC as an indicator for the NO_3-N status of soils.

Materials and methods

Soil samples were collected from August 11 to September 5, 2007 on vegetable fields in the Yangtze River Delta (China). Vegetables were grown in open fields or under foil tunnels. Sampling locations of both cultivation systems were neighboring sites with similar soil characteristics in the vicinity of the cities Yixing, Yangzhou, Zhenjiang, Suzhou, and Changzhou (Table 1, Figure 1). The mean field size was 0.2 ha. The soil samples were selected on basis of characteristic soil types, vegetable rotations, length of vegetable cultivation and N fertilizer input. The total N fertilizer input varied between 370 kg/ha N and 1110 kg/ha N in foil tunnel systems (with a mean N expenditure of 630 kg/ha N); in open fields between 240 and 670 kg/ha N were applied (with a mean N expenditure of 440 kg/ha N).

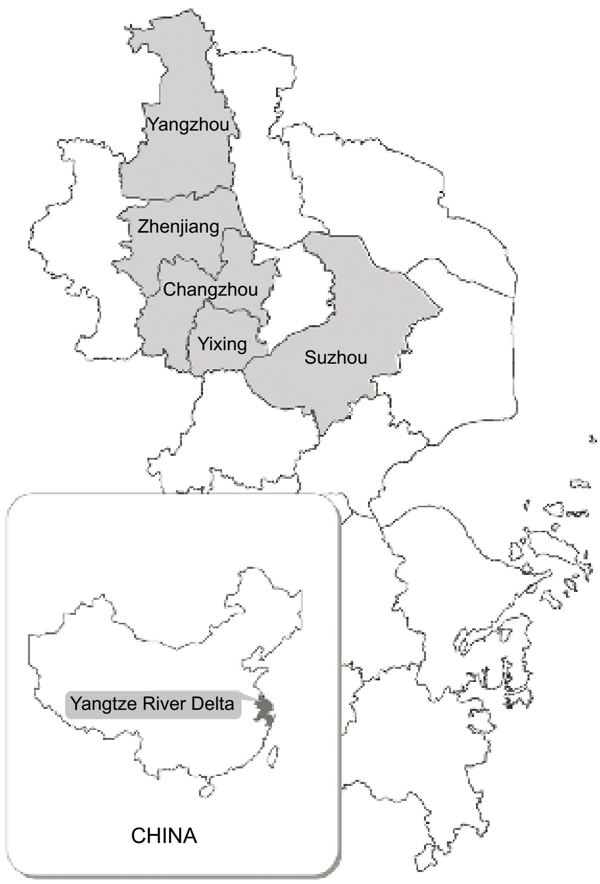

Figure 1:
Location of the investigation area in the Yangtze River Delta in China

At each sampling location one soil profile sample (0 to 10 cm, 10 to 20 cm, 20 to 30 cm) was taken together with 8 to 10 topsoil samples (0 to 10 cm). Soils were air-dried and passed through a 2 mm and then 0.15 mm sieve for the analysis of organic matter and total N; for the determination of soil electrical conductivity (EC), pH, and NO_3-N, NH_4-N soils were ground to a particle size of < 0.75 mm (Lu, 1999).

Table 1:

Distribution of soil samples collected on different vegetable fields in relation to cultivation practice in five cities in the Yangtze River Delta

City	Position (N,E)	(n) Open field	(n) Foil tunnel
Yixing	31° 22' N, 119° 49' E	10	9
Yangzhou	32° 39' N, 119° 42' E	10	10
Zhenjiang	32° 11' N, 119° 27' E	9	9
Suzhou	32° 20' N, 121° 20' E	8	8
Changzhou	32° 16' N, 120° 17' E	8	8
Total		45	44

For chemical soil analysis standard analytical procedures had been employed (Lu, 1999). Soil pH was determined potentiometrically in a soil:water suspension of 1:2.5 (w/v). Soil organic carbon was analyzed after oxidation by potassium dichromate and the organic matter content (OMC) was calculated by multiplying with 1.724. Soil electric conductivity (EC) was measured in a 1:5 (w/v) water extract with an electric conductivity meter (Kang Yi Corp., China). The semi-micro *Kjeldahl* method was employed for the determination of total N (N_t). Soil NO_3-N and NH_4-N was extracted by 2 M KCl solution in a 1:10 ratio (w/v); NO_3-N was determined by spectrophotometry at dual-wavelength (220 nm and 275 nm), and NH_4-N colorimetrically by indophenol blue.

For the ANOVA and t-test of the SPSS statistical package Version 13.0 was employed.

Results

Influence of cultivation practice, soil depth and provenance on pH, electrical conductivity and nitrogen fractions in soil

The results of soil analysis are summarized in Table 2. Cultivation practice had no significant influence on soil pH and soil organic matter content. In comparison, in soils under foil tunnels EC values and NO_3-N, NH_4-N, N_t (total N) concentrations were higher than in open fields. This differ-

Table 2:

Influence of vegetable cultivation practice on soil pH, EC, OMC, NO_3-N, NH_4-N, and N_t content

	Sample set		pH	EC (µS/cm)	NO_3-N	NH_4-N (mg/kg)	N_t	OMC (g/kg)
Foil tunnel	EC < 500 (n=32)	max	7.8	498.0	86.3	114.6	262.8	36.7
		min	5.0	135.0	22.6	4.4	43.0	10.9
		mean	6.5	298.9	60.4	17.9	175.7	24.9
	EC > 500 (n=12)	max	7.5	1554.0	88.4	146.8	264.9	31.8
		min	4.6	538.0	71.9	6.0	112.9	17.9
		mean	6.1	898.7	80.3	34.2	196.4	25.5
	All samples (n=34)	max	7.8	1554.0	88.4	146.8	264.9	36.7
		min	4.6	135.0	22.6	4.4	43.0	10.9
		mean	6.4	462.5	65.9	22.4	181.3	25.1
Open field	EC < 500 (n=41)	max	7.9	480.0	74.3	109.0	246.0	36.5
		min	5.1	72.0	16.8	2.6	63.9	12.2
		mean	6.5	214.6	48.5	14.0	163.9	22.8
	EC > 500 (n=4)	max	6.3	681.0	79.6	78.0	246.8	29.9
		min	5.2	564.0	76.9	8.8	137.8	25.4
		mean	5.8	626.0	78.0	35.1	183.3	27.7
	All samples (n=45)	max	7.9	480.0	74.3	109.0	246.0	36.5
		min	5.1	72.0	16.8	2.6	63.9	12.2
		mean	6.5	214.6	48.5	14.0	163.9	22.8
p	EC < 500		0.99	0.0009	0.0133	0.38	0.31	0.14
	EC > 500		0.48	0.015	0.20	0.97	0.65	0.23
	All samples		0.78	0.0003	0.0006	0.21	0.12	0.13

Note: differences between treatment means are significant at $p < 0.05$

ence was most pronounced for NO_3-N (Table 2). Most striking was the fact that the NO_3-N content was significantly higher in soils with an EC value of > 500 µS/cm when foil tunnel systems were used for vegetable growing.

A classification of samples based on the critical EC value of 500 µS/cm (Li, 1993) revealed that 35 % of all samples from foil tunnels exceeded this threshold, while the corresponding percentage was only 9 % in open field cultivation (Table 2). A strongly negative impact of secondary salinization going along with EC values of > 1000 µS/cm (Li, 1993) was determined in 11 % of all soil samples from foil tunnels.

The influence of cultivation practice on EC and NO_3-N was consistent in all soil profiles and most pronounced in the two upper soil layers (Table 3).

Within the soil profile EC values decreased continuously from the top to deeper soil layers irrespective of the cultivation practice (Table 3), though differences were somewhat smaller in open fields.

Differences in EC between cultivation areas (Table 1) were pronounced and decreased in the following order: Changzou > Suzhou > Yangzhou, Zhenjiang and Yxing (Figure 1). The highest soil EC value was determined in soil samples from foil tunnels in Changzhou and this is most likely related to the time period of cultivating vegetables (Figure 2 and 3).

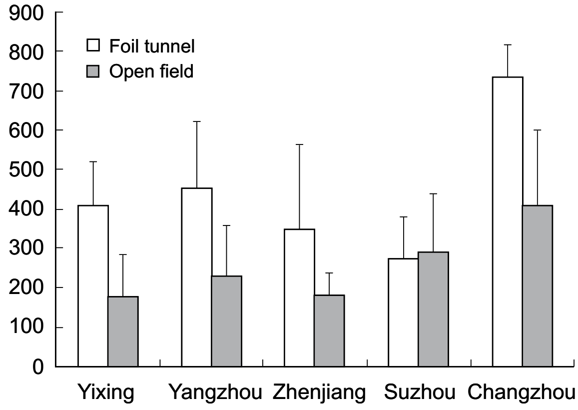

Figure 2:

Variation of soil EC values in relation to vegetable cultivation practice in the vicinity of the cities Changzou, Suzhou, Yangzhou, Zhenjiang and Yixing in the Yangtze River Delta

Table 3:

Variation of pH, EC, NO_3-N, NH_4-N and N_t in different soil depths in relation to cultivation practice in five vegetable cultivation areas in the Yangtze River Delta

Cultivation practice		Soil depth (cm)	pH	EC (µS/cm)	NO_3-N	NH_4-N (mg/kg)	Nt
Foil tunnel	max	0-10	7.83	1554	88.41	146.75	264.86
	min		4.60	135	20.04	4.38	42.97
	mean		6.38	462	64.88	22.36	181.35
Open field	min	0-10	7.88	681	79.62	108.99	246.75
	max		5.10	72	16.80	2.65	63.89
	mean		6.43	251	51.09	15.87	165.58
	p		0.78	0.0003	0.0006	0.21	0.12
Foil tunnel	max	10-20	7.85	444	77.10	9.41	210.35
	min		5.33	149	27.67	5.37	72.87
	mean		6.35	273	51.86	7.33	140.05
Open field	max	10-20	7.78	358	74.93	9.69	152.36
	min		5.85	112	21.17	3.47	64.90
	mean		6.75	186	36.58	7.11	119.15
	p		0.55	0.25	0.28	0.87	0.52
Foil tunnel	max	20-30	7.84	319	68.84	8.56	98.98
	min		6.25	155	20.78	1.84	40.46
	mean		6.81	206	34.98	4.36	71.45
Open field	max	20-30	7.79	170	50.31	8.77	168.11
	min		6.64	80	11.79	4.38	43.89
	mean		7.26	121.4	27.35	6.41	89.23
	p		0.27	0.04	0.53	0.19	0.48

Note: differences between treatment means are significant at $p < 0.05$

Soil EC values increased with the time period of cultivating (Figure 3). On an average the critical threshold of 500 µS/cm was hit after 5 years of continuous vegetable growing. From then onwards soils were objected to secondary salinization. Macroscopic symptoms became visible as white salt spots in the soil surface. Their number and size increased over time.

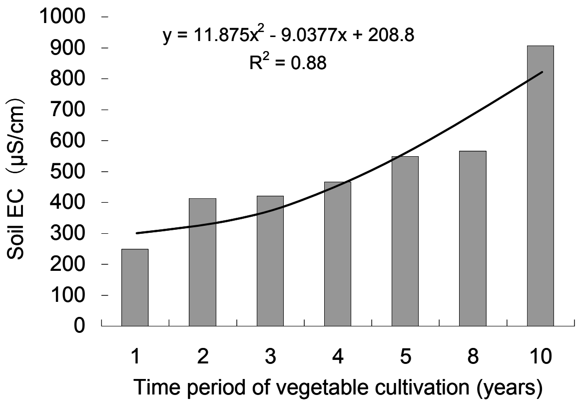

Figure 3:

Relationship between time period of vegetable cultivation and soil EC values in foil tunnel systems

Relationship between soil electrical conductivity and nitrogen fractions in soil

Soil samples were divided into two sets, one with EC values of < 500µS/cm, and one with soil EC values > 500 µS/cm. A highly significant, positive correlation existed between soil NO_3-N and EC in soils that are not affected by secondary salinization ($p < 0.001$) independent of the cultivation practice, while no correlation was found in soils affected by secondary salinization (Figure 4; Table 4). The correlation coefficient was higher in foil tunnel systems where 50 % of the variability of EC could be explained by variations in the NO_3-N content of the soil, while the corresponding values was 32 % in open fields. The results reveal that NO_3-N is a major contributor to soil EC in soils that are not yet affected by secondary salinization.

No significant relationship existed between soil EC and soil NH_4-N, and soil N_t for both cultivation practices (Table 4). Thus the influence of NH_4-N on soil EC seems negligible though in soils under foil tunnels up to 9 % of N was abundant as NH_4-N and in open fields up to 10 % (Table 1). Besides that the temporal variability of NH_4-N is high as nitrobacteria oxidize NH_4-N into NO_3-N within a couple of days (Zhu and Wen, 1992).

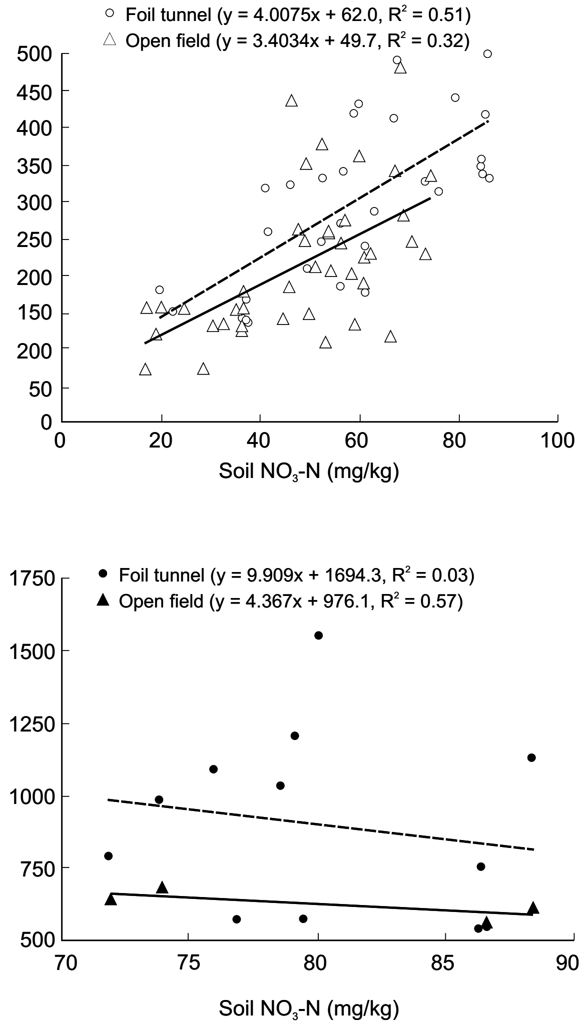

Figure 4:

Relationship between soil NO_3-N content and EC readings in relation to cultivation practice and salinity level (EC < or > 500 µS/cm)

OMC is a sink for nutrients through binding in organic and mineral form as is CEC, for which a positive correlation with OMC was documented (Xiong and Li, 1990). There was a significant, positive correlation between soil OMC and soil EC in soils under cover, while none was found in open fields (Table 4). A possible explanation for these differences might be substantial leaching of nutrients under field conditions.

Discussion

Only a restricted number of investigations are available, which determined the influence of cultivation practices on secondary salinization in agricultural soils of the Yangtze River Delta. The present study suggests that N was leached under open field conditions and thus is one component counteracting secondary salinization. Another relevant factor, which favors salinization, is temperature. Higher

Table 4:

Correlation coefficients for the relationships between soil EC and NO_3-N, NH_4-N, N_t and OMC in relation to vegetable cultivation practice

Cultivation practice	Sample set	NO_3-N	NH_4-N	N_t	OMC
Foil tunnel	EC <500 (n=32)	0.71***	0.27	- 0.11	0.53**
	EC > 500 (n=12)	- 0.17	0.11	0.22	0.16
	All samples (n=44)	0.57***	0.27	0.13	0.50**
Open field	EC <500 (n=41)	0.57***	0.13	0.11	- 0.03
	EC > 500 (n=4)	- 0.62	0.41	0.64	0.84
	All samples (n=45)	0.68***	0.33*	0.19	0.19

Note: **, *** significance level at p < 0.01 and p < 0.001, respectively

temperatures in foil tunnels increase evapotranspiration and amplify salt accumulation in the topsoil layer. A third relevant factor is the fertilization level. Application rates proved to be two to three times higher in foil tunnel systems than in open fields (Cao et al., 2004). When compared to paddy fields fertilizer rates were even four to five times higher (Cao et al., 2004).

The present study and that of Huang et al. (2003) revealed that vegetable cultivation in foil tunnels caused secondary salinization on one third of the experimental sites. Using this form of cultivation soils will reach the critical EC value of 500 µS/cm within about five years (Figure 3). Thus it is recommended to give up foil tunnels in favor of open field cultivation latest after four years in order to avoid secondary salinization. The fact that EC values of > 1000 µS/cm were found after < 3 to 9 years of continuous vegetable cropping under foil tunnel systems indicates that not only the cultivation practice itself, but also excessive fertilizer applications contributed to the problem (Figure 3 and 4). The mean N fertilizer rate applied to vegetables grown in foil tunnels was 1351 kg/ha N, which is about 820 kg/ha higher than the estimated N demand (Liu, 2008). The mean N fertilizer rates in open fields vary between 366 kg/ha for root vegetables, 460 kg/ha for leafy vegetables, and 495 kg/ha for solanaceous vegetables (Chen, 2006), but the actual N demand is only about 75, 120 and 200 kg/ha N (Chen et al., 2003). The unavoidable side effects of disproportionate N surpluses are besides secondary salinization increased losses of N to the environment in form of gaseous NO_x emissions (Li and Wang, 2007) and leaching of nitrate and eutrophication of water bodies (Shi et al., 2009). From agronomic point of view impairment of crop productivity can be expected when EC values exceed 500 µS/cm (Li, 1993). However, already beyond this critical value excessive NO_3 will accumulate favorably in leaves. In leafy vegetables cultivated in foil tunnels NO_3 concentrations of up to 1448 mg/kg were found in the Shanxi province of China (Wang, 2002).

The present study showed that soil EC values proved to be an adequate indicator for the NO_3-N status in vegetable cultivation, particularly in foil tunnel systems and if fields are not yet affected by secondary salinization. A significant positive relationship between soil EC and soil NO_3-N was confirmed in the present study (Figure 3) and other field experiments (Cao et al., 2004; Ju et al., 2007; Shi et al., 2008 and 2009).

Investigations in the field of Precision Agriculture revealed that one factor, which influences the salt content in the soil is the concentration of soluble nutrients (Cockx et al., 2004). Geo-electric sensors are used for establishing on-the-go soil salinity maps (Corwin and Plant, 2005; Lilienthal et al., 2005) and Cockx et al. (2004) used EC readings for variable rate input of N. Site-specific nutrient management on paddock scale, which may span an acreage of only 500 m^2 in China (Hu et al., 2004) is a promising approach to add value to vegetable products by improving crop quality, maintaining crop productivity, inhibiting/ameliorating secondary salinization and reducing avoidable nutrient losses to the environment.

At this point it may be suggested to employ EC sensors for establishing a recommendation system, which is based on instant *in situ* EC measurements and N fertilizer recommendations, which match the site and crop-specific demand in intensive vegetable cultivation areas in order to improve crop productivity and quality and to limit adverse effects of excessive N rates. He et al. (2007) demonstrated that site-specific N fertilization reduced the N input by up to 80 % without any negative impact on crop productivity. The necessity to calibrate sensor data with soil analytical data shall not be left unmentioned here (Lilienthal et al., 2005). Such cheap and effective system could for instance be implemented as one code for good agricultural practice (GAP). GAP codes are a set of simple rules for agricultural practice with high impact for reducing agrochemical losses (Paulsen et al., 2002). It is of prime relevance for the protection of the water bodies and a prerequisite for sustainable agricultural production to reduce non-point nutrient losses (particularly N and phosphorus). In the Lake Erhai Basin of Dali in China, the contribution of N to basin pollution achieved meanwhile a level of 97 % (He, 2005;

Yang, 2004). In 2007, it was calculated for China that only the NH_4-N discharge from rivers to Sea was 84.2×10^4 tons; municipal sewage contributed with 41.5×10^4 tons to about 50 % of the problem, while the other half has to be attributed to losses from agriculture (Anon, 2007). This means that the strict limitation of agricultural non-point pollution is a key factor for controlling and improving water pollution worldwide. Another option to reduce N surpluses is a regular change of land use. This implies vegetable cultivation in the field rather than under foil tunnels, and substitution of vegetable by versatile crop rotations. A positive side effect of land use change combined with reduced N input is decreased acidification (Hu et al., 2006; Xu, 1980).

Conclusions

The results of the present study reveal that soil electrical conductivity (EC) is an opportune indicator for the soil NO_3-N status in intensive vegetable cultivation. In addition, the results showed that foil tunnel systems drastically enhance the problem of secondary salinization last but not least because of a multiple higher fertilizer input when compared to cultivation of vegetables in open fields and other crop plants. Eutrophication of water bodies is a worldwide problem and GAP codes have been established in many countries for reducing non-point nutrient losses. In China, GAP codes have been developed for the cultivation of medicinal plants (Leung and Cheng, 2008), but for agricultural production so far only singular measures have been proposed for individual crop plants and regional agro-environmental conditions (Zhang and Gao, 2008; Wang et al., 2006).

EC measurements in the laboratory or by geo-electric sensors in the field offer the chance to adapt N fertilizer recommendations to the plant available N pool in the soil. Consequently N input can be balanced and N surplus reduced efficiently. EC measurements are a proactive measure against secondary salinization besides a legally restricted cultivation period of vegetables under foil tunnels. Most important with view to sustainable agricultural production is, however, the professional education of farmers. The understanding of the farmer as the biological interface, which safeguards the nutritional status of crops is vital for recognizing the need for professional training as only then traditional fertilizer practices will be replaced by site-specifically adjusted fertilizer rates, which match the actual nutrient demand of the crop (Haneklaus and Schnug, 2006).

Acknowledgments

This project was financially supported by Key Project of Knowledge Innovation Program, Chinese Academic of Sciences (KSCX2-YW-N-038) and it was part of the Sino-German bilateral co-operation.

References

Anon (2007) China statistical yearbook. National Bureau of Statistics of China

Anon (2007) Report on the state of the environment in China 2007. Ministry of Environmental Protection of China

Arkady G, Jacob B (1994) The influence of free convection on soil salinization in arid region. Transport Porous Media 23:275-301

Barica J (1972) Salinization of groundwater in arid zones. Water Res 6:925–933

Cao ZH, Huang JF, Zhang CS, Li AF (2004) Soil quality evolution after land use change from paddy soil to vegetable land. Environ Geochem Health 26:97-103

Chen JZ, Kang QX, Zhang QX (2003) The nutrient status of vegetable fields and balance fertilization for vegetables. Plant Nutrition Fertilizer Science (in Chinese) 9:117-122

Chen Q, Zhang XS, Zhang HY (2004) Evaluation of current fertilizer practice and soil fertilizer in vegetable production in the Beijing region. Nutr Cycl Agroecosystems 69:51-58

Chen XP, Zhang FS (1996) The problems and countermeasures of vegetable fertilization in Beijing. J China Agric Univ 1(5):63-66

Chen YM (2006) Problems of fertilizer application in vegetables of Lishui county in China. Modern Agricultural Technology (in Chinese) 7:52-55

Cockx L, Van Meirvenne M, Hofman G (2004) The use of electromagnetic induction in delineating nitrogen management zones. In: Proceedings of the 7th International Conference on Precision Agriculture and Other Precision Resources Management, July 25-28, 2004, Minneapolis, MN USA. Madison : ASA-CSSA-SSSA [CD-Rom]

Corwin DL, Plant RE (2005) Applications of apparent soil electrical conductivity in precision agriculture. Comput Electron Agric 46:1-397

Corwin DL, Rhoades JD, Simunek J (2007) Leaching requirement for soil salinity control : steady state versus transient models. Agric Water Manage 90:165–180

Du LF, Zhang WL, Li ZH (2006) Soil quality with various planting patterns in Yangtze River Delta Area (in Chinese). J Agro-Environ Sci 25:95-99

Ghassemi F, Jakeman AJ, Nix HA (1995) Salinisation of land and water resources : human causes, extent, management and case studies. Wallingford : CAB International, 526 p

Haneklaus S, Schnug E (2006) Site-specific nutrient management : objectives, current status and future research needs. In: A Srinivasan (ed) Handbook of precision agriculture : principles and applications. New York : Food Products Press, pp 91-134

He R-M, Zhang J-Y, Lu G-H (2005) The trend of study on non-point source pollution. J China Hydrol 25:10-14

He FF, Chen Q, Jiang RF, Chen X, Zhang FS (2007) Yield and nitrogen balance of greenhouse tomato (Lycopersicum esculentum Mill.) with conventional and site-specific nitrogen management in northern China. Nutr Cycl Agroecosystems 77:1-14

Hollger E, Baginska B, Cornish PS (1998) Factors influencing soil and nutrient loss in storm water from a market garden [online]. Zu finden in <http://www.regional.org.au/au/asa/1998/ß/182hollinger.htm> [zitiert am 27.05.2009]

Hu ZH, Haneklaus S, Liu Q, Xu C, Cao Z, Schnug E (2003) Small-scale spatial variability of phosphorus in a paddy soil. Commun Soil Sci Plant Anal 34:2791-2801

Hu ZY, Wang CR, Cao ZH (2006) Migration of nitrogen and phosphorus from vegetable soils to water system. In: Cao ZH, Lin XG (eds) Substance exchange in soil-water system and water environment quality in Tai-lake Basin (in Chinese). Beijing : Science Press, pp 118–138

Huang JF, Cao ZH, Lian F, Zhang CS (2003) Soil fertility quality evolution after land use change from rice-wheat rotation to plastic film covered vegetable (in Chinese). Plant Nutr Fertilizer Sci 9:19-25

Ju XT, Kou CL, Christie P, Dou ZX, Zhang FS (2007) Changes in the soil environment from excessive application of fertilizers and manures to two contrasting intensive cropping systems on the North China Plain. Environ Pollut 145:497–506

Lesch M, Rhoades JD, Lund LJ, Corwin DL (1992) Mapping soil salinity using calibrated electromagnetic measurements. Soil Sci Soc Am J 56:540–548

Leung PC, Cheng KF (2008) Good agricultural practice (GAP) : does it ensure a perfect supply of medicinal herbs for research and drug development? Int J Appl Res Natural Prod 1:1-8

Li HY, Xing YX, Wang XF (2001) Research progress in control measure of nitrate accumulation in vegetable (in Chinese). Changjiang Vegetable 4:8-10

Li D, Wang XM (2007) Nitric oxide emission from a typical vegetable field in the Pearl River Delta, China. Atmos Environ 41:9498-9505

Li XL, Zhang FS (2002) The fertilizer utilization of vegetable production in China. In: Li XL, Zhang FS Fertilizing for sustainable production of high quality vegetable (in Chinese). Beijing : China Agric Univ Press, pp 270-277

Li XZ, Wang YL, Zhang ZB (1993) Research on accumulation of salt ions of greenhouse vegetable land in Beijing suburb (in Chinese). China Vegetable 4:15-17

Lilienthal H, Ponomarev M, Schnug E (2004) Application of LASSIE to improve agricultural field experimentation Landbauforsch Völkenrode 54(1):21-26

Liu ZH (2000) Characteristics of greenhouse vegetable soil and reasonable fertilization in Shandong Province (in Chinese). Beijing : Agric Univ, pp 35-40

Liu ZH, Jiang LH (2008) Evolution of fertilization rate and variation of soil nutrient contents in greenhouse vegetable cultivation in Shandong. Acta Pedol Sin 45(2):296-303

Lu RK (1999) Soil sample analysis (in Chinese). In: Lu RK Soil agriculture chemistry analysis method. Beijing : Agriculture Science Press of China, pp146-163

Maxted JT, Diebel MW (2008) Landscape planning for agricultural non–point source pollution reduction : II Balancing watershed size, number of watersheds, and implementation effort. Environ Manage 43(1):60-68

Paulsen HM, Volkgenannt U, Schnug E (2002) Contribution of organic farming to marine environmental protection. Landbauforsch Völkenrode 52(4):211-218

Power JF, Schepers JS (1989) Nitrate contamination of groundwater in North America. Agric Ecosyst Environ 26:165–187

Roades JD (1982) Soluble salts. In: Page AL (ed) Methods of soil analysis : part 2, chemical and microbiological properties. Madison, Wis :Am Soc Agron, pp167-179

Shi WM, Yao J, Yan F (2008) Vegetable cultivation under greenhouse conditions leads to rapid accumulation of nutrients, acidification and salinity of soils and groundwater contamination in South-Eastern China. Nutr Cycl Agroecosystems 83:73-84

Stigter TY, Ooijen SPJ, Post VEA, Applello CAJ, Dill AMMC (1998) A hydrogeological and hydrochemical explanation under irrigated land in a Mediterranean environment, Algarve, Portugal. J Hydrol 208:262–279

Tanji KK (1990) Nature and extent of agricultural salinity In: Tanji KK (ed) Agricultural salinity assessment and management. New York : American Society of Civil Engineers, pp 71-92, ASCE manuals and reports on engineering practice 71

Wang H, Dong YH, Li DC (2005) Nutrient variation in plastic greenhouse soils with the years of cultivation (in Chinese). Soils 37:460-466

Wang X, Tao LX, Tan HJ, Cheng SH (2006) Innovating rice farming systems, ensuring food and environments safety. Scientia Agricultura Sinica 39:1984-1991

Wang ZH, Zong ZQ, Li SX, Chen BM (2002) Nitrate accumulation in vegetables and its residual in vegetable field (in Chinese). Environ Sci 23(3):79-83

Wells AT, Chan KY, Cornish PS (2000) Comparison of conventional and alternative vegetable farming systems on the properties of a yellow earth in New South Wales. Agric Ecosyst Environ 80:47-60

Xiong Y, Li QK (1990) Organic matter of soil (in Chinese). In: Soils of China (in Chinese). Beijing : Science Press, pp 206-232

Xu Q, Zhu HG (1980) Physical and cemical poperties of the paddy soil of Taihu region (in Chinese). In: Xu Q, Lu YC, Liu YC, Zhu HG The paddy soil of Taihu region in China. Shanghai : Shanghai Sience & Technology Press, pp 1-98

Yang J-Y (2004) Non-point source pollution and water quality deterioration in Er Hai Lake Yunnan. Environ Sci 23:104-105

Zhang DL, Gao QS (2008) Application of good agricultural practice on vegetable sites – based on panel data and linguistic information processing for agricultural produce safety evaluation. J China Agric Univ 13:105-110

Zhu ZL, Wen QX (1992) Transformation of nitrogen in soil (in Chinese). In: Zhu ZL, Wen QX Nitrogen in the Chinese soil. Jiangsu : Scientific and Technology Publishing House, pp 5-30