Long-distance transport of alkali metals in maturing wheat

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Abstract

The alkali metals cesium, rubidium, lithium and sodium were introduced together with strontium via flaps into leaf laminas or into the stem of maturing, intact winter wheat (*Triticum aestivum* L. cv. Arina) grown in a field. Long-distance transport of these elements and the influence of the application date and of different application positions were investigated. The phloem-immobile Sr served as a marker for the distribution of the xylem sap in the plants. Dry matter accumulation in the grains and the transpiration per shoot were not markedly affected by the treatments as compared to control plants. The phloem mobility was rather high for Cs and Rb. Li was almost immobile in the phloem (similarly to Sr). An application into the cut stem xylem below the second leaf node contributed more to the contents in the grains than an application into the flag leaf. An earlier feeding date led to a higher accumulation in the grains. The marked losses of the elements applied during maturation (most pronounced for Li) can be explained by leakage in the rain.

Additional key words: accumulation, grains, lithium, mobility, phloem, potassium, rubidium, sodium, strontium, *Triticum aestivum*, xylem.

Introduction

Strontium is a phloem-immobile, xylem-mobile element (Feller 1989, Schenk and Feller 1990, Kuppelwieser and Feller 1991a, Marschner 1995, Zeller and Feller 1999) and it indicates the distribution of the xylem sap in the plant (Kuppelwieser and Feller 1991a,b). Therefore Sr serves as a marker for xylem transport (Schenk and Feller 1990, Herren and Feller 1997a,b, Zeller and Feller 1999). Foliar applied Sr is absorbed by the leaf, but not exported from the leaf and therefore considered immobile in the phloem of bean (Bukovac and Wittwer 1957). Sr was mainly translocated with the transpiration stream to the glumes of detached wheat ears, which have been standing in Rb and Sr for 3 d (Kuppelwieser and Feller 1990). In intact wheat shoots, Sr introduced via a stem flap below the flag leaf node can be detected at a later stage of maturation in various shoot parts, especially in the glumes and in the leaf lamina which are organs with a high transpiration rate (Herren and Feller 1997b). The risk of a redistribution of Sr from contaminated leaves into other plant organs is low, but a contamination of edible plant parts from the soil is possible due to transport in the xylem from roots to the shoot (Zehnder *et al.* 1993). The foliar uptake of radioactive Sr into plants is

rather low and represents therefore a minor risk for the consumers of fruits as compared to Cs (Zehnder *et al.* 1996). Only traces of the applied radioactive Sr is taken up by the leaves of grapevine plants and there is essentially no redistribution within the plant (Zehnder *et al.* 1995).

Rb is easily transported in the xylem and in the phloem (Feller 1989, Kuppelwieser and Feller 1991a,b, Marschner 1995). Therefore Rb can serve as a marker for phloem mobile solutes (Schenk and Feller 1990, Herren and Feller 1997a,b). In bean leaves, applied Rb is readily absorbed and is highly mobile in the phloem (Bukovac and Wittwer 1957). Rb is rapidly eliminated from the xylem sap and accumulates in the lower part of the stem of detached wheat ears standing for 3 d in a solution containing Rb and Sr (Kuppelwieser and Feller 1990). In intact wheat shoots, Rb introduced via a flap into the stem accumulates in the grains (Herren and Feller 1997b).

K is characterized by a high mobility in plants at all levels: within individual cells, within tissues and in long-distance transport via the xylem and phloem (Marschner 1995). K is a mineral nutrient which is required in large amounts by plants and it is in general the

most abundant cation in the cytoplasm of plants (Marschner 1995). In bean, foliar applied K is readily absorbed by the leaf and is highly mobile in the phloem (Bukovac and Wittwer 1957). In detached wheat ears, K is easily unloaded from the xylem and transferred to the phloem (in internodes) during its acropetal transport (Haeder and Beringer 1984a). Such a transfer from the xylem to the phloem was also detected for some heavy metals (Zeller and Feller 1998) and for Cs ions (Feller *et al.* 2000). In intact wheat plants, uptake of labelled K into the shoot depends on the K concentration applied (Haeder and Beringer 1984b). The results from these experiments show further that the low and uniform K content found generally in the grain dry matter seems to be due to a controlled K supply to the ear. In maize, xylem loading of K is regulated separately from K uptake from external solution (Engels and Marschner 1992). Furthermore, the adaptation of K translocation to the demand of the shoot is coupled with an altered capacity of the root for xylem loading.

In bean leaves, applied Na is readily absorbed and is highly mobile in the phloem (Bukovac and Wittwer 1957). Na is an essential mineral element only for some plants (Marschner 1995). After a mild salinity treatment, soybean showes a marked retention of Na in the stems and a low transport to the laminas of young leaves (Durand and Lacan 1994). This indicates a protection of the young leaves from Na accumulation by depletion of Na from the xylem stream.

Alkali metals are the elements of the first group of the periodic table of the elements. The aim of the work presented here was to compare the relative mobility, the transport and retranslocation of the alkali metals from the flag leaf lamina and from the stem xylem to the developing grains in maturing wheat. The experiment focus mainly on Cs. The other alkali metals Li, Na, K and Rb as well as the marker Sr (element of the second group of the periodic table of the elements) are included to allow comparison. The application position and the application date are considered for the accumulation in the grains and for the relative contributions to the final contents in the harvested grains.

Materials and methods

Winter wheat (*Triticum aestivum* L., cv. Arina) was grown under natural conditions in a field in Zollikofen near Berne. The plants for this experiment were treated in the field between June 13, 1996 (anthesis) and July 30, 1996 (final harvest).

Flaps have been cut with a razor blade according to Schenk and Feller (1990) either in the lamina of the flag leaf or in the stem below the second node from the top of the plant. With this technique, 1 cm^3 solution was introduced from a tube directly into the cut xylem. The solution in these tubes contained Cs, Li and Na, as well as Sr and Rb which served as markers for xylem and phloem transport. The feeding solution contained 0.5 mM CsCl, 5 mM LiCl, 5 mM NaCl, 5 mM $SrCl_2$ and 5 mM RbCl. This solution was taken up by the plants within one

day when fed into the stem and within one to three days when fed into a leaf lamina.

The plants were collected throughout the maturation period, dissected and dried at 105 °C. The dry mass of the grains and the number of grains were determined. The different plant parts were heated separately in an oven at 550 °C for several hours. The ash was solubilized in 0.25 cm^3 HCl. After mixing, deionized water (2.25 cm^3) was added. The sample solutions were diluted with 0.1 M HCl (for Cs), 36 mM $LaCl_3$ in 0.1 M HCl (for Sr) and 7.52 mM CsCl in 0.1 M HCl (for Li, Rb, Na and K). The Cs, Li, Rb, Sr, Na and K contents of the different plant parts were measured by atomic absorption spectro-photometer (*AA 1475, Varian Techtron*, Mulgrave, Australia).

Results

The dry matter accumulation in the grains of maturing wheat plants was not or only slightly affected by the introduction of alkali metals and Sr via flaps (data not shown). The difference between the dry mass of the grains of untreated control plants and the dry mass of the grains of treated plants never exceeded 27 %. This indicated that cutting the flaps and the introduction of solutes had no major consequence on maturation and grain filling.

An introduction of Cs into the flag leaf or into the stem below the second leaf node from the top led to

nearly the same content of Cs in the grains, but a different distribution of Cs within the other plant parts was observed (Fig. 1). When Cs was introduced into the flag leaf lamina, the contents in the application leaf (flag leaf) decreased. This was paralleled by an increase in the Cs content of the grains. Cs was rapidly translocated via the phloem from the leaves to the grains indicating that Cs is highly mobile in the phloem. In the stem above the application leaf, Cs could also be detected but only in minor quantities. In the other parts of the ear (glumes, rachis) and in the plant parts below the application

position, Cs could only be detected in trace amounts. Cs introduction into the stem below the second leaf node from top of the plant caused an increase in the content in the grains throughout the maturation period while the Cs content in leaf 1 and leaf 2 decreased during this time interval. In the stem above the feeding position, Cs was also detected in minor quantities. After application into the stem, only trace amounts of Cs were detected in the rachis and in the plant parts below the application position. An earlier feeding date resulted in a higher accumulation of Cs in the grains (Table 1). The distribution of Cs was similar to that of Rb (Fig. 1, Table 1). Rb served as a marker for solutes with a high phloem mobility.
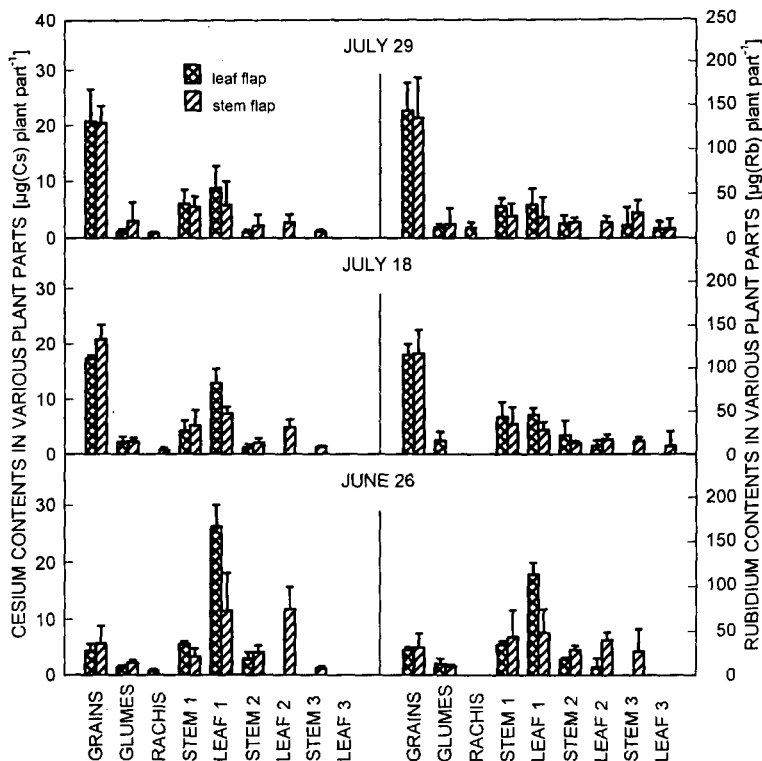

Fig. 1. Distribution of cesium and rubidium in intact wheat plants. The plants were fed via a flap into the flag leaf lamina or into the stem below the second leaf node from top of the plant on June 13. The feeding solution (1 cm^3) contained 5 mM RbCl, 5 mM SrCl$_2$, 5 mM LiCl, 5 mM NaCl and 0.5 mM CsCl. The *vertical bars* represent standard deviations of 4 replicates for samples collected on June 26, July 18, and July 29.

In contrast to Cs and Rb (Fig. 1, Table 1), Li was not or only in minor quantities transported to the grains (Fig. 2). An introduction into the stem led to higher Li contents within the plant than an introduction into the flag leaf. When Li was introduced into the flag leaf, the highest contents could be detected in this leaf whereas only minor quantities were below or above this application position. This indicated a low phloem mobility for Li. The Li contents in the application leaf (flag leaf) decreased to about 22 %. A marked increase however was not observed in other plant parts. This strongly suggested a major loss of Li. An introduction into the stem led to decreases in leaf 2 (about 80 %) and in leaf 1 (about 60 %). A very small quantity was detected in the grains and in stem 1. From these results it can be concluded that Li was only in minor quantities retranslocated via the phloem to the grains. An earlier introduction into the stem led to a slightly higher accumulation of Li in grains (Table 1). On the other hand, an earlier introduction into the leaf caused no marked effects on the contents in the grains. This indicates that Li was not or only in very small quantities retranslocated via the phloem.

The results for Li were similar to the results for Sr (Fig. 2, Table 1). Sr introduced into the leaf led to no redistribution which indicated a very low phloem mobility for Sr. Introduction of Sr into the stem (Fig. 2) indicated a rapid transport via xylem to the grains. Sr is a marker for the distribution of the xylem sap in a plant. The losses of Sr were less pronounced than the losses observed for Li (Table 1). This may be due to a better solubility or a better accessibility of Li for the rain water (Schenk and Feller 1990, Debrunner and Feller 1995).

The content of K in unfed wheat plants was about 25 % higher than in the plants supplied with the alkali metals (Fig. 3). This indicated that the treatment (cutting the flaps and introduction of alkali metals) interferred slightly with the K dynamics. An introduction of alkali metals into the flag leaf led to about the same

accumulation of K in the grains as an introduction into the stem. The content in the lower plant parts decreased. This indicated a good redistribution from the lower parts to the grains via xylem and phloem. The contents of the grains were much higher (up to 11-fold) than the content of the glumes. The results for K were quite similar to those for Cs and Rb (Fig. 1, Table 1). In contrast to K, Na was not as rapidly transported to the grains (Fig. 3). Therefore the retranslocation of Na from the lower parts to the grains was less efficient than for K. The content of Na in the grains was – in contrast to K – about the same as the content in the glumes. It can be concluded that the quantity of the Na introduced via a flap into the wheat plants was too small (compared to the Na which was already present) to allow a more specific investigation of the redistribution of this element from the application position to the grains.

Table 1. Cesium, rubidium, lithium, and strontium contents [μg shoot^{-1}] in grains of intact wheat plants. The plants were fed via a flap into the flag leaf lamina or into the stem below the second leaf node from top of the plant on June 13, June 19, June 26, July 3 or July 11. The feeding solution (1 cm^3) contained 5 mM RbCl, 5 mM SrCl$_2$, 5 mM LiCl, 5 mM NaCl and 0.5 mM CsCl. Means and standard deviations of 4 replicates. The contents in the grains of unfed control plants on June 26 were <0.1 μg shoot^{-1} for Li, <1 μg shoot^{-1} for Cs and <10 μg shoot^{-1} for Rb and Sr.

Metal	Date of feeding	Harvest date June 26 flag leaf	stem	July 18 flag leaf	stem	July 29 flag leaf	stem
Cs	June 13	4.4 ± 1.3	5.7 ± 3.1	17.4 ± 0.5	20.8 ± 2.7	20.7 ± 5.8	20.4 ± 3.1
	June 19	2.4 ± 0.8	6.9 ± 0.2	14.6 ± 2.4	15.5 ± 7.0	10.5 ± 2.4	19.5 ± 5.6
	June 26	-	-	10.5 ± 3.9	17.7 ± 3.4	9.8 ± 3.1	19.2 ± 4.0
	July 3	-	-	6.1 ± 2.0	11.7 ± 4.2	11.2 ± 2.3	14.8 ± 5.9
	July 11	-	-	1.6 ± 0.5	3.5 ± 1.2	3.4 ± 1.0	4.8 ± 1.7
Rb	June 13	29 ± 3	32 ± 16	115 ± 13	117 ± 28	144 ± 32	136 ± 46
	June 19	19 ± 7	30 ± 10	97 ± 7	84 ± 48	68 ± 14	121 ± 21
	June 26	-	-	63 ± 18	91 ± 30	52 ± 16	98 ± 17
	July 3	-	-	30 ± 3	42 ± 14	64 ± 24	80 ± 29
	July 11	-	-	29 ± 4	34 ± 15	50 ± 32	28 ± 15
Li	June 13	0.13 ± 0.07	0.74 ± 0.21	0.25 ± 0.11	1.30 ± 0.52	0.38 ± 0.20	1.31 ± 0.11
	June 19	0.13 ± 0.03	0.56 ± 0.20	0.29 ± 0.29	0.81 ± 0.41	0.17 ± 0.11	1.46 ± 0.49
	June 26	-	-	< 0.1	0.96 ± 0.18	0.14 ± 0.05	1.14 ± 0.27
	July 3	-	-	0.28 ± 0.21	0.51 ± 0.16	0.24 ± 0.09	0.84 ± 0.31
	July 11	-	-	0.16 ± 0.04	0.56 ± 0.38	< 0.1	0.66 ± 0.11
Sr	June 13	<10	59 ± 7	<10	79 ± 22	<10	75 ± 15
	June 19	<10	37 ± 5	<10	48 ± 16	<10	61 ± 8
	June 26	-	-	<10	63 ± 18	<10	58 ± 20
	July 3	-	-	<10	60 ± 22	<10	43 ± 14
	July 11	-	-	<10	45 ± 11	<10	35 ± 8

Discussion

The introduction of Cs, Rb, Li, Sr and Na via flaps into maturing wheat did not severely disturb maturation of the plants and grain filling. The results indicated that the mobilities in the phloem were higher for Cs, Rb and K than for Na. Sr and Li were essentially phloem-immobile, but Li was slightly less immobile than Sr. These results are in agreement with previously reported results concerning the relative mobilities of these elements in higher plants (Marschner 1995 and references therein).

From the different application positions it became evident that an application into the cut stem xylem below the second leaf node contributed more to the grain contents than an application into the flag leaf. Transport in the stem via xylem was possible for all elements, whereas transport from the leaves to the grains via phloem was only possible for the phloem-mobile elements as Cs, Rb, K and Na. Generally, an earlier feeding date led to higher accumulations of Cs, Rb, Li and Sr in the grains. Only trace amounts of Cs are present in radioactive fallout (^{134}Cs and ^{137}Cs), while 0.1 mM CsCl (non-radioactive Cs) were applied in these field-experiments to allow a proper quantification by atomic absorptions spectrometry. It was reported previously that the redistribution of ^{134}Cs in wheat shoots is not markedly

affected by the addition of 0.1 mM CsCl to the solution introduced into the wheat plants via a flap (Feller *et al.* 2000). Therefore the general findings reported here may also be relevant for the redistribution of Cs nuclides from radioactive fallout in field-grown wheat. Contamination of the environment with radionuclides can result from

accidents in nuclear power stations (*e.g.* in Chernobyl on April 26, 1986) or from tests of nuclear weapons (Lasat *et al.* 1997). Wet and dry deposition of radionuclides may lead to a contamination of crop plants near the emission site as well as in remote regions (Clark and Smith 1988). As a consequence, radionuclides may be taken up by the
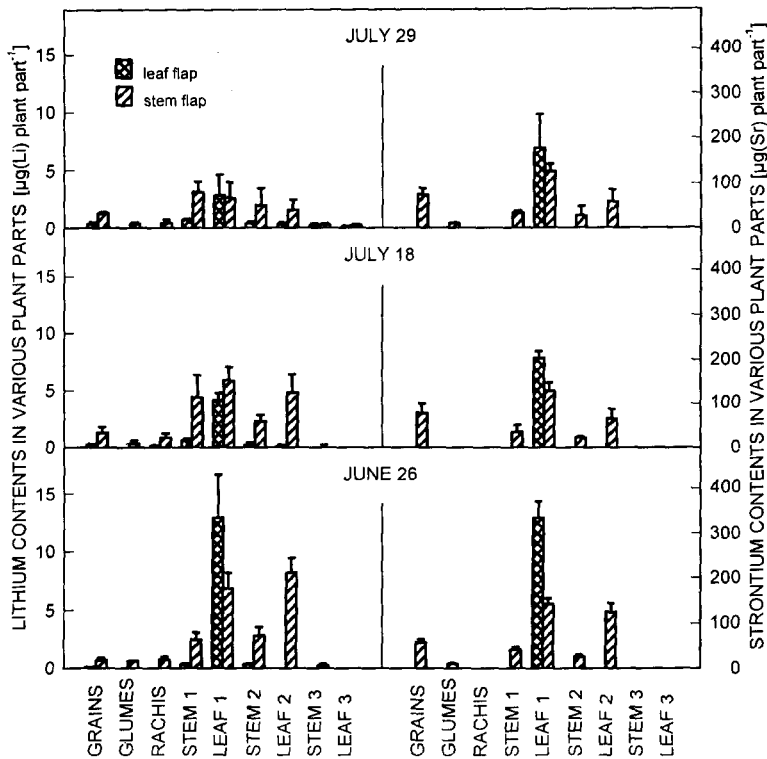

Fig. 2. Distribution of lithium and strontium in intact wheat plants. The plants were fed via a flap into the flag leaf lamina or into the stem below the second leaf node (for detail see Fig. 1).

crop plants via the shoot surface, partially accumulate in the harvested plant parts and enter the food chain. From this point of view, element-specific redistribution processes in maturing wheat and the influence of the application date are highly relevant for the final contents in the harvested grains.

The losses from the whole shoots during maturation were higher for Li and Sr than for Cs and Rb. The losses might be explained by the hypothesis that solutes may be washed out in the rain from senescing plant parts as reported previously (Debrunner and Feller 1995).

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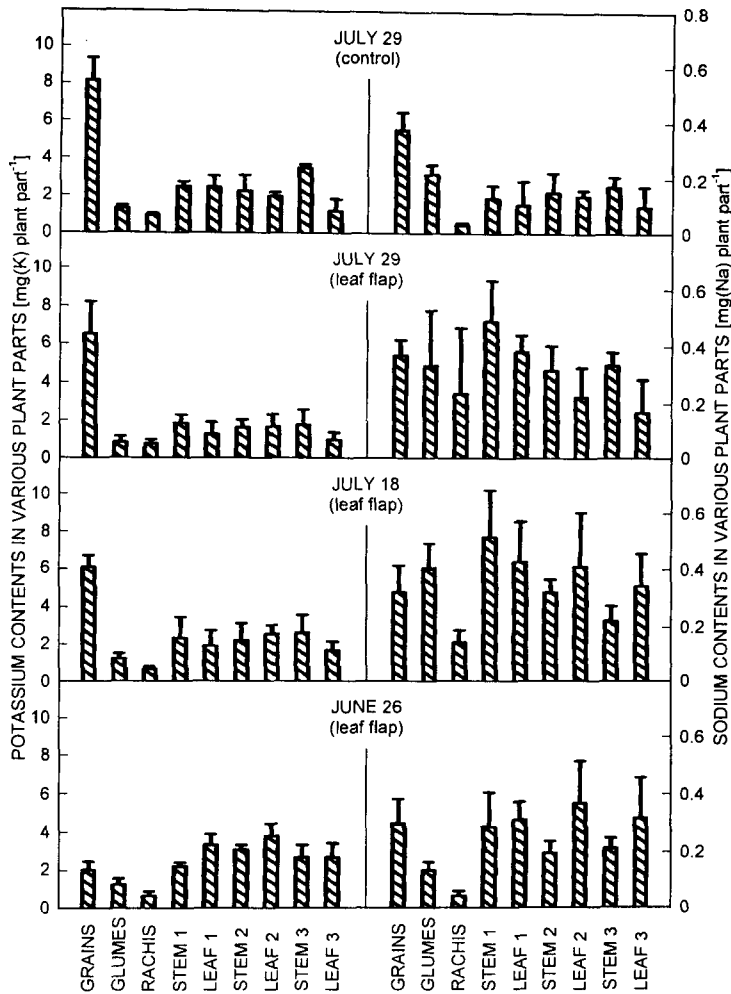

Fig. 3. Accumulation of potassium and sodium in the grains of maturing wheat. The plants were fed via a flap into the flag leaf lamina (for detail see Fig. 1).

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