Society Awards 2022

(for highly prospectiveness/prominent achievement)

Studies on the abilities of uptake and translocation from root to shoot of pesticides in soil

Sayuri Namiki

Institute for Agro-Environmental Sciences, NARO, 3–1–3 Kannondai, Tsukuba, Ibaraki 305–8604, Japan

The uptake experiments with pesticides were performed to clarify differences among plant species, and the influence of growth stages and conditions on the uptake and translocation ability of pesticides. There were 2–10-fold differences among plant species in the root and shoot concentrations of each pesticide, and shoot concentrations of pesticides in *Brassica rapa* L. var. *perviridis* were relatively high. In addition, the changes in shoot concentrations with growth stage of *B. rapa* were affected by root system development. The influence of temperature on uptake and translocation ability differed for each pesticide, while uptake and translocation ability were high for short day lengths. This indicated that plant uptake and translocation of pesticides were affected by root system development and growth conditions such as temperature and day length, not only the relationships to the chemical's properties and behavior of organic chemicals in the soil.

Keywords: pesticides, growth stage, growth conditions, root concentration factor, shoot–root concentration ratio, transpiration stream concentration factor.

Introduction

In Japan, agricultural chemicals used for primary crops and those persisting in soil have been detected in succeeding crops at levels exceeding the maximum residue limits.[1] Affected production areas can be forced to take emergency measures, such as self-imposed halts on shipments or extensive inspection of soils and crops. It is necessary to clarify the plant uptake of organic chemicals to prevent problems such as crop contamination.

The plant uptake of organic chemicals is generally explained by relationships to the chemical's properties, especially those that determine the logarithm of the *n*-octanol–water partition coefficient ($\log K_{OW}$). In a hydroponic experiment, as hydrophobicity increased ($\log K_{OW}$ increased), organic chemicals were concentrated in roots, while the relationship between translocation to shoots and $\log K_{OW}$ produced a bell-shaped curve.[2–5] Based on the relationship between chemicals' $\log K_{OW}$ and accumulation in roots or translocation to aboveground tissues *via*

xylem, a number of plant uptake models for organic chemicals have been developed.[6–11]

In addition, several studies of organic chemical uptake in soil have focused on relationships between plant concentrations and the behavior of organic chemicals in soil.[12,13] Despite plant growth stage and conditions having important effects on plant physiological reactions, the influence of these on pesticide uptake has not been investigated. The purposes of our studies were to clarify differences among plant species, and the influence of different growth stages and growth conditions on the uptake and translocation ability of pesticides. Here, I review the results of our research.

1. Differential uptake and translocation of pesticides by several plant species[14]

There are numerous screening data concerning the concentration in soils and residue in crops or vegetables of pesticides applied to soils. However, these screenings focus on pesticide residues in edible parts, and so the parts with concentrations measured differ, in some cases in fruit and in other cases leaves and stems. Moreover, in these screenings, the cultivation periods differ with the different growing speeds of crops or vegetables, so the periods of pesticide uptake from soils by plants also differ. In our study, we investigated the differences in pesticide concentrations in root and shoot using 16 plant species under the same growing conditions. The tested plants were grown for the same period (21 days) in the soil to which was applied the 10 tested

Table 1.   Physicochemical properties of pesticides.

Chemicals	Pesticide type	Substance group	Octanol–water partition coefficient (log K_{OW})		
			a)	b)	c)
Dinotefuran	Insecticide	Neonicotinoid	−0.549	−0.549	−0.549
Imidacloprid	Insecticide Veterinary substance	Neonicotinoid	0.57	0.57	0.57
Clothianidin	Insecticide	Neonicotinoid	0.7	0.7	0.905
Thiacloprid	Insecticide Molluscicide	Neonicotinoid	0.74	1.26	1.26
Fosthiazate	Insecticide Nematicide	Organophosphate	1.68	1.68	1.68
Metalaxyl	Fungicide	Phenylamide	1.75	1.75	1.65
Fenobucarb	Insecticide	Carbamate	2.67	2.67	2.78
Procymidone	Fungicide	Dicarboximide	3.14	3.30	3.3
Flutolanil	Fungicide	Phenylbenzamide	3.17	3.77	3.17
Tolclofos-methyl	Fungicide	Chlorophenyl	4.56	4.56	4.56

a) Values obtained from The Pesticide Manual (16th ed.).[15] b) Values obtained from The 2011 Pesticide Handbook.[16] c) Values obtained from the Footprint Pesticide Database of IUPAC.[17] Reprinted from Ref. 14.

Table 2.   Concentration of pesticides in shoots and roots for each plant.

Plants	Concentration (mg/kg-DW)									
	Dinotefuran	Imidacloprid	Clothianidin	Thiacloprid	Fosthiazate	Metalaxyl	Fenobucarb	Procymidone	Flutolanil	Tolclofos-methyl
Shoot										
Hordeum distichon L.	5.03 def	0.32 cde	0.86 ef	0.11 abc	0.47 ab	1.04 abc	0.24 a	2.11 f	0.15 a	<0.02
Zea mays L.	4.06 cde	0.21 abc	0.31 abc	0.13 bcd	2.90 bc	2.37 c	0.95 a	1.66 ef	0.57 b	<0.02
Glycine max Merrill	4.76 def	0.36 de	0.05 a	0.20 de	1.55 abc	2.41 c	0.58 a	1.85 ef	<0.02	<0.02
Phaseolus vulgaris L.	0.66 a	<0.02 a)	<0.02	<0.02	0.62 ab	0.13 a	0.14 a	0.26 a	<0.02	<0.02
Brassica oleracea L. var. *capitata*	9.52 g	0.54 fg	0.81 def	0.47 g	3.15 c	2.47 c	0.24 a	2.09 f	0.05 a	<0.02
Brassica rapa L. var. *peruviridis*	6.22 f	0.38 de	0.88 f	0.27 e	1.47 abc	0.87 ab	0.15 a	2.20 f	<0.02	<0.02
Chrysanthemum coronarium L.	8.53 g	1.10 h	1.35 g	0.68 f	12.70 e	9.29 d	4.80 b	0.98 cd	0.86 c	0.06 b
Lactuca sativa L.	0.67 a	0.14 a	0.07 a	0.05 ab	0.12 a	0.26 ab	<0.02	0.35 ab	0.04 a	<0.02
Allium wakegi Araki	4.23 de	0.29 bcd	0.52 cd	0.02 a	1.02 abc	0.10 a	0.57 a	2.07 f	0.41 b	<0.02
Apium graveolens L. var. *dulce*	5.65 ef	0.27 abcd	0.55 cd	0.11 abc	7.69 d	1.09 abc	5.74 b	0.20 a	<0.02	0.04 ab
Solanum lycopersicum Mill.	5.39 ef	0.60 g	0.57 cde	0.15 cd	0.99 abc	0.04 a	0.54 a	1.82 ef	0.12 a	<0.02
Capsicum grossum L.	3.44 bcd	0.44 ef	0.22 ab	<0.02	0.45 ab	0.20 a	0.08 a	1.26 de	0.04 a	<0.02
Cucumis sativus L.	2.58 bc	0.24 abcd	0.28 abc	0.09 abc	0.77 ab	0.93 ab	0.37 a	1.62 ef	<0.02	0.03 a
Cucurbita maxima Duch.	2.40 b	0.24 abcd	0.20 a	0.12 bcd	2.30 abc	1.36 abc	1.24 a	0.89 bcd	<0.02	<0.02
Spinacia oleracea L.	6.11 f	0.56 fg	1.54 g	<0.02	0.14 a	0.10 a	0.05 a	0.42 abc	0.12 a	<0.02
Beta vulgaris L. var. *cicla*	5.04 def	0.17 ab	0.49 bc	0.03 a	1.56 abc	1.68 bc	0.15 a	0.90 bcd	0.17 a	<0.02
Root										
Hordeum distichon L.	0.16 abc	0.03 a	0.03 a	0.03 a	0.07 abc	0.06 a	0.15 ab	0.24 ab	0.21 ab	0.04 a
Zea mays L.	0.39 d	0.07 bc	0.05 ab	0.07 abcd	0.20 bcde	0.20 cd	0.28 abc	0.53 ab	0.33 ab	0.40 a
Glycine max Merrill	0.16 abc	0.20 d	0.13 c	0.33 e	0.17 de	0.39 f	0.39 abc	1.37 abc	0.21 ab	0.70 a
Phaseolus vulgaris L.	0.29 cd	0.08 bc	0.06 ab	0.12 d	0.12 abcd	0.17 bc	0.15 ab	0.63 abc	0.05 a	0.34 a
Brassica oleracea L. var. *capitata*	0.10 ab	0.06 abc	0.04 a	0.08 bcd	0.06 a	0.07 a	0.17 ab	0.46 ab	0.26 ab	0.57 a
Brassica rapa L. var. *peruviridis*	0.11 ab	0.05 abc	0.04 a	0.07 abc	0.08 abc	0.11 ab	0.12 a	0.39 ab	0.26 ab	0.31 a
Chrysanthemum coronarium L.	0.06 ab	0.07 bc	0.05 ab	0.09 cd	0.26 ef	0.07 a	8.96 e	14.08 e	4.19 d	34.22 b
Lactuca sativa L.	0.12 ab	0.08 c	0.03 a	0.04 ab	0.07 abc	0.09 a	0.04 a	0.66 abc	0.39 ab	0.66 a
Allium wakegi Araki	1.24 e	0.17 d	0.15 c	0.09 bcd	0.32 f	0.27 de	1.59 abcd	1.78 abc	0.85 bc	0.74 a
Apium graveolens L. var. *dulce*	0.41 d	<0.02	<0.02	<0.02	0.18 cde	0.07 a	2.05 d	5.01 d	0.41 ab	3.58 a
Solanum lycopersicum Mill.	0.27 cd	0.07 bc	0.06 ab	0.08 bcd	0.11 abcd	0.12 ab	0.10 a	0.55 abc	0.39 ab	0.42 a
Capsicum grossum L.	0.27 cd	0.04 ab	0.03 a	0.03 a	0.06 ab	0.06 a	0.16 ab	0.26 ab	0.18 ab	0.20 a
Cucumis sativus L.	0.05 a	0.06 abc	0.03 a	0.08 abcd	0.32 f	0.35 ef	1.76 bcd	2.48 c	1.41 c	2.34 a
Cucurbita maxima Duch.	0.20 bc	0.06 abc	0.06 ab	0.08 abcd	0.59 g	0.50 g	1.86 cd	2.17 bc	0.94 bc	2.02 a
Spinacia oleracea L.	0.07 ab	0.08 c	0.08 b	0.07 abc	<0.02	0.10 ab	0.09 a	0.73 abc	0.20 ab	0.16 a
Beta vulgaris L. var. *cicla*	0.07 ab	0.06 abc	0.05 ab	0.05 abc	0.04 a	0.06 a	0.11 a	0.21 a	0.04 a	0.11 a

Data were compared using one-way ANOVA followed by Tukey's multiple comparison test ($p<0.05$). Within a column, means followed by the same letter are not significantly different. a) Under the detection limit. Reprinted from Ref. 14.

pesticides which have wide $\log K_{OW}$ level (Table 1), and the concentrations in roots and shoots were compared.

As the results, there were 2–10-fold differences among plant species in the root and shoot concentrations of each pesticide (Table 2). Notably, the shoot concentrations of leafy vegetables such as *Brassica rapa* L. var. *perviridis* and *Chrysanthemum coronarium* L. were higher than those in the other plant species. Therefore, was used *B. rapa* as a test plant to compare the influence of growth stage and growth conditions on the uptake and translocation abilities of four of the pesticides with relatively high values of $\log K_{OW}$: fenobucarb, procymidone, flutolanil, and tolclofos-methyl.

2. Relationship of growth stage of *B. rapa* and pesticide-uptake ability[18]

The relationships between $\log K_{OW}$ and the ability of uptake or translocation were obtained *via* hydroponic experiments. The experiments had a short exposure time for organic chemicals and ignore the influence of plant growth, such as increased biomass. In addition, hydroponic experiments using precultured plants to take up organic chemicals did not show the influence of plant growth stage on the uptake and translocation ability of organic chemicals. When considering cropping systems, for example *B. rapa* which requires 30–60 days from sowing to harvesting, plants take up pesticides for a longer period than in hydroponic experiments. It is also possible that the uptake and translocation ability of pesticides are affected by plant growth and pesticide behavior in soil. The relationships between plant growth stage and pesticide-uptake ability were investigated *via* *B. rapa* cultivation in soil to which four pesticides (fenobucarb, procymidone, flutolanil, and tolclofos-methyl) were added.

2.1. Relationships between growth stage and pesticide concentrations in root and shoot

In the experiment, plant growth conditions remained the same from sowing onward, and the plant growth stage used was the vegetative stage from sowing to harvest. The *B. rapa* seedlings progressed from having only cotyledons to having two major leaves at 10 days and 2–4 major leaves at 18 days after sowing. These growth stages represent the first and second thinning-out periods for *B. rapa* cultivation. At the usual stage of harvesting (32–39 days after sowing) the seedlings had 8–16 major leaves; at 60 days, seedlings had 29–32 major leaves and had passed the appropriate stage of harvesting for food.

The root concentrations of fenobucarb, procymidone, and flutolanil were lowest at 10 days and highest at 18 days after sowing (Table 3). The root concentrations of the four pesticides tended to decrease gradually during 25–60 days after sowing. The root concentrations of tolclofos-methyl tended to increase during 10–18 days after sowing but did not change significantly. In ad-

Table 3.   Concentrations of pesticides in roots, shoots, and soil solution for each cultivation period.

Day after sowing	Concentrations			
	Fenobucarb	Procymidon	Flutolanil	Tolclofos-methyl
Root (mg/kg-DW)				
10 days	0.03±0.01 b	0.11±0.04 b	0.16±0.04 b	0.34±0.06 ab
18 days	0.16±0.03 a	0.37±0.06 a	0.52±0.06 a	0.69±0.11 a
25 days	0.12±0.02 ab	0.36±0.07 ab	0.32±0.05 ab	0.47±0.08 ab
32 days	0.12±0.02 ab	0.34±0.03 ab	0.29±0.02 b	0.40±0.04 ab
39 days	0.11±0.01 ab	0.25±0.04 ab	0.26±0.04 b	0.36±0.06 ab
60 days	0.08±0.01 ab	0.18±0.01 ab	0.18±0.01 b	0.15±0.01 b
Shoot (mg/kg-DW)				
10 days	0.14±0.02 bc	1.06±0.12 b	0.030±0.005 b	0.020±0.002 a
18 days	0.74±0.11 a	2.45±0.58 ab	0.083±0.020 a	0.022±0.006 a
25 days	0.53±0.04 ab	2.62±0.17 a	0.086±0.007 a	0.016±0.001 a
32 days	0.46±0.03 abc	2.42±0.11 ab	0.065±0.003 ab	0.013±0.000 a
39 days	0.40±0.01 abc	2.01±0.04 ab	0.054±0.003 ab	0.009±0.000 a
60 days	0.06±0.00 c	1.45±0.13 ab	0.017±0.002 b	<0.002[a]
Mean concentrations in soil solution (µg/L)				
10 days	398.95	28.66	64.14	0.88
18 days	369.50	25.99	57.99	0.79
25 days	345.52	23.85	53.09	0.73
32 days	323.09	21.90	48.61	0.66
39 days	302.12	20.10	44.50	0.61
60 days	247.03	15.54	34.15	0.47

Data were compared using one-way ANOVA followed by Tukey's multiple comparison test ($p<0.01$). Within a column, means followed by the same letter are not significantly different. [a] Under the detection limit. Reprinted and partially modified from Ref. 18.
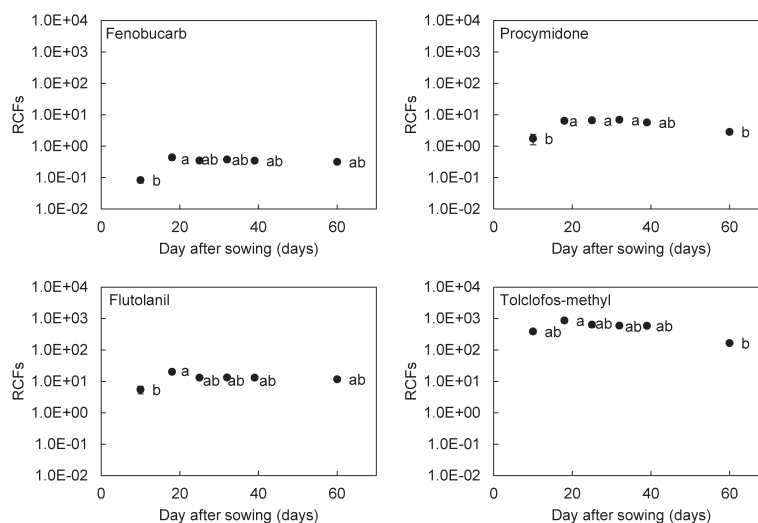
Fig. 1. Root concentration factors (RCFs) of pesticides for time after sowing. Error bars indicate SEM ($n=4$). Data were analyzed by one-way ANOVA followed by Tukey's multiple comparison test ($p<0.01$). The same letters indicate that values do not significantly differ. Reprinted from Ref. 18.

dition, root concentrations of tolclofos-methyl tended to be lowest at 60 days after sowing. The shoot concentrations of fenobucarb, procymidone, and flutolanil were low at 10 days, high at 18 or 25 days, and declined until 60 days after sowing. Concentrations of tolclofos-methyl did not significantly differ in shoots during 10–39 days after sowing, and tolclofos-methyl was not detected at 60 days after sowing.

2.2. Influence of growth stage on pesticide uptake and translocation abilities

The concentration of pesticides in soil solution decreased immediately after adding pesticides to soil and continued to change with time after sowing (Table 3). The bioconcentration factor is widely used to compare the uptake and translocation ability for cases of different concentrations in the medium.[19] In addition,

it is assumed that plant roots take up organic chemicals including pesticides, from the soil through the soil solution.[20,21] We used the root concentration factor (RCF) calculated by dividing the concentration in roots by the concentration in the soil solution to compare the uptake ability in each plant growth stage (Fig. 1). The RCF values of tested pesticides were constant 18–39 days after sowing, and then the pesticide-uptake ability of roots did not change from when the seedlings had 2–4 major leaves to the usual harvesting period. Therefore, we concluded that the decreasing trend for root concentrations of pesticides during this period was due to decreasing concentrations in the soil solution, not decreasing uptake ability by plants for physiological reasons. However, the low RCF values at 10 days after sowing indicated that *B. rapa* had lower pesticide-uptake ability at the seedling stage than at other growth stages. The 10-day period after sowing was soon
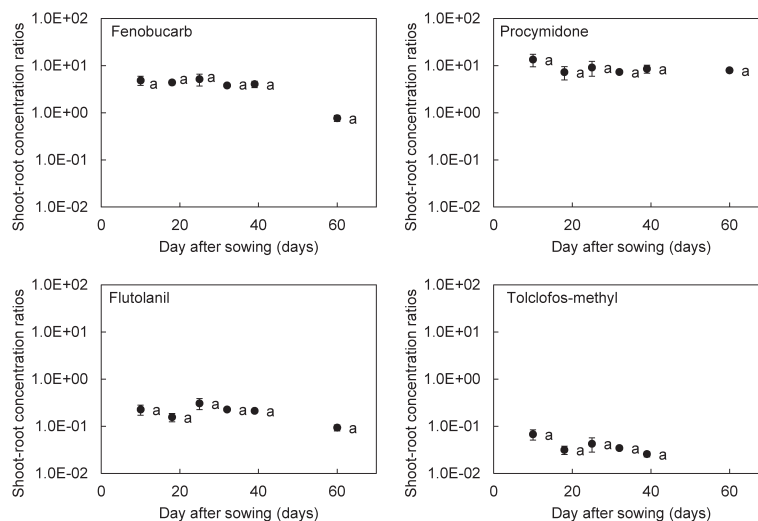

Fig. 2. Shoot–root concentration ratios of pesticides for time after sowing. Error bars indicate SEM ($n=4$). Data were analyzed using a one-way ANOVA followed by Tukey's multiple comparison test ($p<0.01$). The same letters indicate that values do not significantly differ. Reprinted from Ref. 18.

after germination, so the root systems were not as developed as at 18 days. This indicates that root development was an important factor affecting pesticide-uptake ability from soil.

The translocation ability from root to shoot were compared by using the shoot–root concentration ratio, calculated by dividing shoot concentration by root concentration.[14] Although the shoot–root concentration ratios of the pesticides for 60 days after sowing tended to decrease, they did not significantly differ (Fig. 2). It was confirmed that tested pesticides were distributed to shoots at a constant rate after being taken up by roots, regardless of growth stage. Therefore, the low pesticide concentrations in newly germinated *B. rapa* shoots were caused by the low uptake ability of pesticides by the root and not difficulty in root–shoot translocation. These results suggest that root system development was important for translocation from soil solution to the shoot and affected changes in the pesticide concentration in shoots.

3.   Influence of *B. rapa* growth conditions on plant uptake of pesticides[22]

Brassica rapa were cultivated in soil mixed with four pesticides (fenobucarb, procymidone, flutolanil, and tolclofos-methyl) at different temperatures (15, 20, and 25°C), day lengths (8, 12, and 16 hr), and soil water contents (60%, 75%, and 90% water holding capacity). Then it was compared the influence of plant growth conditions on the uptake and translocation ability of pesticides.

3.1.   Pesticide concentrations in root and shoot for each growth condition

The pesticide concentrations in shoots and roots are shown in Table 4. Although the root concentrations of tolclofos-methyl did not significantly differ among growth conditions, the concentrations of the other pesticides in roots at 25°C were higher

Table 4   Concentrations of pesticides in roots, shoots, and soil solution for each growth condition.

Treatment		Concentrations			
		Fenobucarb	Procymidon	Flutolanil	Tolclofos-methyl
Root (mg/kg-DW)					
Temperature	15°C	0.10±0.01 ab	0.44±0.03 ab	0.32±0.02 a	0.43±0.01 a
	20°C	0.08±0.01 a	0.26±0.04 a	0.22±0.03 a	0.35±0.04 a
	25°C	0.17±0.02 b	0.67±0.06 b	0.66±0.07 b	0.33±0.02 a
Day length	8 hr	0.16±0.01 b	0.66±0.06 b	0.64±0.06 b	0.40±0.03 a
	12 hr	0.08±0.01 a	0.26±0.04 a	0.22±0.03 a	0.35±0.04 a
	16 hr	0.08±0.01 a	0.31±0.03 a	0.26±0.03 a	0.32±0.03 a
Soil water contents	60%	0.08±0.01 a	0.26±0.04 a	0.22±0.03 a	0.35±0.04 a
	75%	0.18±0.01 b	0.53±0.02 a	0.47±0.03 b	0.40±0.03 a
	90%	0.14±0.02 ab	0.54±0.07 a	0.45±0.04 ab	0.55±0.04 a
Shoot (mg/kg-DW)					
Temperature	15°C	1.47±0.13 b	2.08±0.15 a	0.081±0.006 a	0.007±0.0007 a
	20°C	0.73±0.08 a	2.34±0.24 a	0.059±0.010 a	0.008±0.0007 a
	25°C	0.49±0.01 a	2.89±0.13 a	0.073±0.003 a	0.006±0.0006 a
Day length	8 hr	1.40±0.08 b	3.34±0.15 b	0.145±0.007 b	0.012±0.0009 b
	12 hr	0.73±0.08 a	2.34±0.24 a	0.059±0.010 a	0.008±0.0007 ab
	16 hr	0.65±0.02 a	2.21±0.05 a	0.046±0.001 a	0.007±0.0003 a
Soil water contents	60%	0.73±0.08 a	2.34±0.24 a	0.059±0.010 a	0.008±0.0007 a
	75%	0.58±0.13 a	4.38±0.18 b	0.135±0.019 b	0.008±0.0003 a
	90%	0.65±0.08 a	4.30±0.12 b	0.119±0.009 ab	0.012±0.0007 a
Mean concentrations in soil solution (μg/L)					
Temperature	15°C	365.28	34.89	84.22	1.39
	20°C	318.07	21.06	46.57	0.62
	25°C	252.46	18.65	46.86	0.64
Soil water contents	60%	318.07	21.06	46.57	0.62
	75%	316.08	25.33	74.52	1.06
	90%	281.21	23.29	61.32	1.09

Data were compared using one-way ANOVA followed by Tukey's multiple comparison test ($p<0.01$). Within a column, means followed by the same letter are not significantly different. Reprinted and partially modified from Ref. 22.

than at 15°C and 20°C, and were high for the 8-hr photoperiod compared to other photoperiods. In addition, the root concentrations of fenobucarb and flutolanil tended to increase with rising soil water contents. The fenobucarb concentration in shoots at 15°C was higher than at 20°C and 25°C. However, the concentrations of procymidone, flutolanil, and tolclofos-methyl in shoots did not significantly differ with temperature. The shoot concentrations of the four pesticides were high for short days. The shoot concentrations of procymidone and flutolanil tended to increase with rising soil water content.

3.2.   Effects of growth conditions on uptake and translocation abilities of pesticides

Because the mean concentrations of pesticides in soil solution differed according to temperature and soil water content (Fig. 4), the influence of growth conditions on root uptake ability of pesticides was compared using RCFs (Fig. 3).

The RCFs of fenobucarb, procymidone, and flutolanil were high for 25°C compared to other temperatures. Because plant roots can be considered as sorbents of pesticides, sorption to roots might be promoted at 25°C. In addition, the root weight and transpiration rate are regarded as plant physiological factors that influence the uptake of organic chemicals.[23] At 25°C, although the root dry weight did not differ from those at other temperatures, the transpiration rate that equaled the uptake amount of the water by the root was high. Therefore, the root uptake of these pesticides might have increased with the sorption of pesticides to roots, and the amount of water taken up may have been promoted at 25°C. In addition, the RCFs of these three pesticides were high for the 8-hr (*i.e.*, short day) photoperiod compared with other photoperiods. The root dry weight and transpiration rate were low for the short days, indicating that these factors did not affect the uptake ability of pesticides. If metabolism were promoted by long days, the pesticides might

be metabolized in roots. As a result, root concentrations might decrease under long days, and the RCFs would be low. Consequently, the RCFs of these pesticides might be relatively high for short days. Moreover, the RCFs of these pesticides tended to increase with rising soil water content. These pesticides are more easily dissolved in water than tolclofos-methyl. Thus, the amount of water taken up might make a larger contribution to the uptake of these pesticides than for tolclofos-methyl, and thus the RCF increased under conditions of high soil water content due to a high transpiration rate. The RCF of tolclofos-methyl was not affected by growth conditions, and it is likely that plant physiological factors such as transpiration rate and metabolism did not influence the uptake ability for tolclofos-methyl.

Organic chemicals are translocated from root to shoot through the xylem by the transpiration stream. Thus, the transpiration stream concentration factor (TSCF) is widely used to describe the translocation of organic chemicals to shoots.[2–5] The TSCF is defined as the ratio of the concentration in the xylem sap to that in the medium.[2] It is difficult to directly measure the concentration in xylem sap, and so we estimated it by dividing the amount of pesticide in the shoot by the volume of water transpired[24,25] (Fig. 4).

The TSCF of fenobucarb was high for the 15°C treatment, but the TSCF of procymidone increased with rising temperature. The TSCF of flutolanil did not significantly differ with temperature, indicating that temperature had little or no effect on its translocation to the shoot. The TSCF of tolclofos-methyl was high for 20°C and had no clear relationship with temperature. The above results suggest that the relationship between translocation ability and temperature varied according to the pesticide. Concerning the effect of photoperiod, the TSCFs of the four tested pesticides were higher for short days. Thus, pesticide metabolism in the shoot could be a plant physiological factor that lowered the TSCF, as also suggested for the RCF. Although the
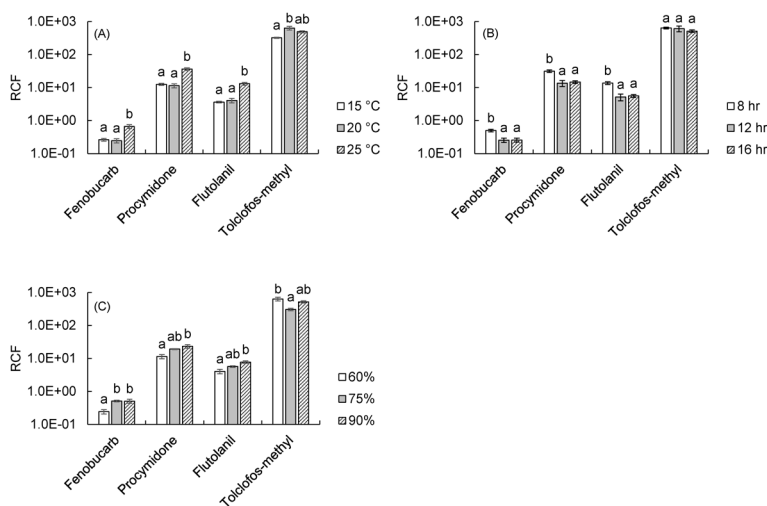

Fig. 3.   Root concentration factors (RCFs) of pesticides for (A) temperature, (B) day length, and (C) soil water contents. Error bars indicate SEM (*n*=4). Data were analyzed by one-way ANOVA followed by Tukey's multiple comparison test (*p*<0.01). Bars with the same letter are not significantly different. Reprinted from Ref. 22.
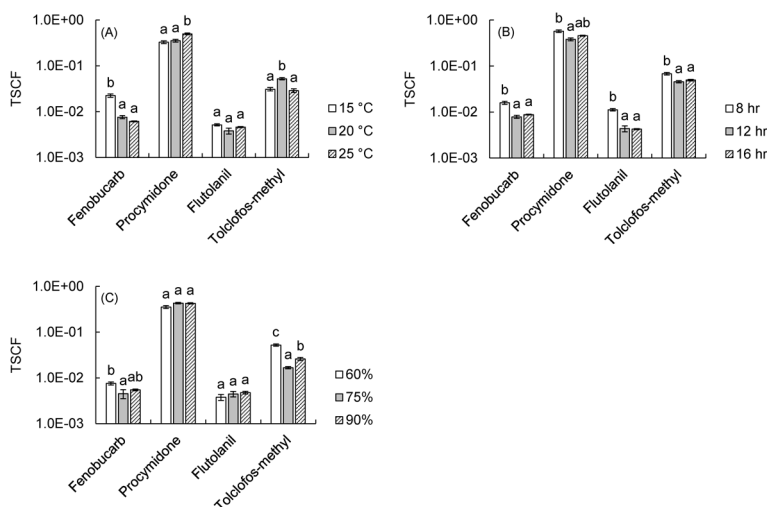
Fig. 4. Transpiration stream concentration factors (TSCFs) of pesticides for (A) temperature, (B) day length, and (C) soil water contents. Error bars indicate SEM ($n=4$). Data were analyzed by one-way ANOVA followed by Tukey's multiple comparison test ($p<0.01$). Bars with the same letter are not significantly different. Reprinted from Ref. 22.

TSCFs of tolclofos-methyl were lower for 75% and 90% water holding capacity, the TSCFs of the other three pesticides remained constant for all soil water contents. Thus, translocation of fenobucarb, procymidone, and flutolanil depended on the transpiration rate for soil water treatments. Because tolclofos-methyl is highly hydrophobic, it is difficult to translocate from root to shoot. There might be little tolclofos-methyl in the shoot for the transpiration rate. It is likely that translocation of tolclofos-methyl basically depends on the transpiration rate.

Concluding remarks

Considering plant physiological factors such as root biomass and transpiration rate that may affect uptake and translocation of pesticides from soil, it was investigated the influence of growth stage and growth conditions on the ability of pesticide uptake and translocation. The plant uptake and translocation of pesticides were affected by root system development and growth conditions such as temperature and day length, not only the relationships to the chemical's properties and behavior of pesticides in the soil. However, the changes in abilities of pesticide uptake and translocation for different temperatures or day lengths could not be explained only by difference in biomass and transpiration rate, indicating that pesticide metabolism might be affected by plant physiological factors of uptake and translocation. Further investigation is required to clarify the behavior of pesticides in plant tissues incorporating the perspective of crop cultivation, as for influence of growth conditions on the metabolism of pesticides in plants.

References

1) S. Hori: *Foods Food Ingredients J. Jpn.* **212**, 496–508 (2007) (in Japanese with English summary).
2) G. G. Briggs, R. H. Bromilow and A. A. Evans: Relationships between lipophilicity and root uptake and translocation of non-ionised chemicals by barley. *Pestic. Sci.* **13**, 495–504 (1982).
3) F. C. Hsu, R. L. Marxmiller and A. Y. Yang: Study of root uptake and xylem translocation of cinmethylin and related compounds in detopped soybean roots using a pressure chamber technique. *Plant Physiol.* **93**, 1573–1578 (1990).
4) F. Sicbaldi, G. A. Sacchi, M. Trevisan and A. A. M. DelRe: Root uptake and xylem translocation of pesticides from different chemical classes. *Pestic. Sci.* **50**, 111–119 (1997).
5) J. G. Burken and J. L. Schnoor: Predictive relationships for uptake of organic contaminants by hybrid poplar trees. *Environ. Sci. Technol.* **32**, 3379–3385 (1998).
6) S. Trapp, M. Matthies, I. Scheunert and E. M. Topp: Modeling the bioconcentration of organic chemicals in plants. *Environ. Sci. Technol.* **24**, 1246–1252 (1990).
7) S. Trapp and M. Matthies: Generic one-compartment model for uptake of organic chemicals by foliar vegetation. *Environ. Sci. Technol.* **29**, 2333–2338 (1995).
8) S. Trapp: Plant uptake and transport models for neutral and ionic chemicals. *Environ. Sci. Pollut. Res. Int.* **11**, 33–39 (2004).
9) C. Turgut: Uptake and modeling of pesticides by roots and shoots of parrotfeather (Myriophyllum aquaticum). *Environ. Sci. Pollut. Res. Int.* **12**, 342–346 (2005).
10) C. Collins, M. Fryer and A. Grosso: Plant uptake of non ionic organic chemicals. *Environ. Sci. Technol.* **40**, 45–52 (2006).
11) T. E. McKone and R. L. Maddalena: Plant uptake of organic pollutants from soil: bioconcentration estimates based on models and experiments. *Environ. Toxicol. Chem.* **26**, 2494–2504 (2007).
12) Y. Motoki, T. Iwafune, N. Seike, T. Otani and Y. Akiyama: Relationship between plant uptake of pesticides and water-extractable residue

in Japanese soils. *J. Pestic. Sci.* **40**, 175–183 (2015).

13) F. Clostre, P. Letourmy, B. Turpin, C. Carles and M. Lesueir-Jannoyer: Soil type and growing conditions influence uptake and translocation of Organochlorine (Chlordecone) by Cucurbitaceae species. *Water Air Soil Pollut.* **225**, 2153 (2014).

14) S. Namiki, T. Otani, Y. Motoki, N. Seike and T. Iwafune: Differential uptake and translocation of organic chemicals by several plant species from soil. *J. Pestic. Sci.* **43**, 96–107 (2018).

15) C. MacBean: "The Pesticide Manual," 16th Ed., British Crop Protection Council, Surrey, 2012.

16) The 2011 Pesticide Handbook Editorial Committee: "The 2011 Pesticide Handbook" Japan Plant Protection Association, Tokyo, 2011 (in Japanese)

17) http://sitem.herts.ac.uk/aeru/iupac/ (Accessed 18 Jan., 2017)

18) S. Namiki, T. Otani, Y. Motoki and N. Seike: The influence of *Brassica rapa* var. *perviridis* growth conditions on the uptake and translocation of pesticides. *J. Pestic. Sci.* **43**, 248–254 (2018).

19) J. C. White, Z. D. Parrish, M. Isleyen, M. P. N. Gent, W. Iannucci-Berger, B. D. Eitzer and M. I. Mattina: Influence of nutrient amendments on the phytoextraction of weathered 2,2-bis(p-chlorophenyl)-1,1-dichloroethylene by cucurbits. *Environ. Toxicol. Chem.* **24**, 987–994 (2005).

20) T. E. McKone and R. L. Maddalena: Plant uptake of organic pollutants from soil: Bioconcentration estimates based on models and experiments. *Environ. Toxicol. Chem.* **26**, 2494–2504 (2007).

21) E. L. Miller, S. L. Nason, K. G. Karthileyan and J. A. Pedersen: Root uptake of pharmaceuticals and personal care product ingredients. *Environ. Sci. Technol.* **50**, 525–541 (2016).

22) S. Namiki, N. Seike and Y. Motoki: Relationship between growth stage of *Brassica rapa* var. *perviridis* and the abilities for uptake and translocation of pesticides in soil. *J. Pestic. Sci.* **44**, 1–8 (2019).

23) S. Trapp: Calibration of a plant uptake model with plant- and site-specific data for uptake of chlorinated organic compounds into radish. *Environ. Sci. Technol.* **49**, 395–402 (2015).

24) M. G. T. Shone, O. B. Bartlett and A. V. Wood: A Comparison of the uptake and translocation of some organic herbicides and a systemic fungicide by Barley. *J. Exp. Bot.* **25**, 401–409 (1974).

25) S. Trapp: Modelling uptake into roots and subsequent translocation of neutral and ionisable organic compounds. *Pest Manag. Sci.* **56**, 767–778 (2000).