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FOLIAR INTERCEPTION AND RETENTION VALUES AFTER PESTICIDE APPLICATION. A PROPOSAL FOR STANDARDIZED VALUES FOR ENVIRONMENTAL RISK ASSESSMENT

(Technical Report)

Prepared for publication by
J. LINDERS[1], H. MENSINK[1], G. STEPHENSON[2], D. WAUCHOPE[3], AND K. RACKE[4]

[1]RIVM-CSR, P.O. Box 1, NL-3720 BA Bilthoven, The Netherlands; [2]University of Guelph, Guelph, ON N1G 2W1, Canada; [3]USDA-Agricultural Research Service, P.O. Box 748, Tifton, GA 31794, USA; [4]Dow Agrosciences, 9330 Zionsville Road, Indianapolis, IN 46268, USA

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Abstract: In performing risk assessments for plant protection products by applicants or regulators in relation to the registration of the products, an important aspect to take into account is the foliar interception and retention of the active substance of the product on the plant. An overview is given of the approaches to this item in several parts of the world. The relevant circumstances and influencing variables, such as growth phase, planting density, and some physicochemical characteristics (e.g., vapor pressure and Henry's coefficient) are dealt with. Finally, a proposal is presented for how to take into account the phenomenon of foliar interception and retention in the initial phase, first tier, of the risk assessment process.

1. INTRODUCTION

In the registration process of plant protection products, governmental authorities as well as industrial applicants have to carry out risk assessments to come to decisions on the marketing of products. Several methods are available to perform these risk assessments. Sometimes the risk assessment is carried out on a case-by-case basis, and specific characteristics of the active substance are taken into account, depending on the situation. Generally, guidance documents are used to assist in the assessment procedure, for example, the European Union registration of plant protection products under 91/414/EEC and accompanying annexes [1]. The purpose of the current paper is to describe the methods used for estimating foliar interception and retention and to develop new estimation rules for an appropriate environmental exposure analysis. Especially for the initial stage of the risk assessment (tier 1) it is necessary to know approximate foliar interception values (fraction of spray contacting the foliage) and retention values (fraction of spray retained by the foliage) of the plant for spray combinations of concern. These quantities are fundamental to understanding efficacy, environmental fate, water pollution potential, and nontarget effects of all pesticides applied to foliage of crops and weeds.

The literature on the interception of pesticides by plants mainly deals with agronomic aspects of pesticide use, for example, whether spray equipment and weed control can be improved, or whether such data can be used for making or validating simulation models on crop growth. Therefore, most literature does not aim at determining the fractions of the application rate that are intercepted by the crop—leaves, stems or ears—in relation to the fractions that finally reach the soil [2–4]. However, interception fractions are important input parameters for decision-making schemes that assess the potential or actual environmental risks following the deposition of pesticides on the soils of agroecosystems. Such risks may refer to the leaching to groundwater and the damage to indigenous populations of terrestrial micro- or macro-organisms. An overview of the interception fractions in use for environmental risk assessment in several countries is included in this article. Subsequently, interception data from field studies—and to a much lesser extent from greenhouse studies, as these do not necessarily reflect typical agricultural practices—will be reviewed. Proposals for standard crop- and growth phase-specific interception fractions will be discussed in relation to these field data.

The present study focuses on crop interception rather than on soil deposition assuming that there are more data on the former than on the latter. Subsequently, the extent of soil deposition can be estimated by subtracting the extent of crop interception—and losses via other dissipation routes, if relevant—from the application rate. However, actual experimental data on soil deposition should always be used for verification.

Actual experimental field data on the interception of pesticides by crops are scarce [2] and [4], and therefore a comprehensive overview of the typical interception fractions for the various crops in the Organization for Economic Cooperation and Development (OECD) countries cannot be presented. Besides, various agronomic (e.g., the type of crop cultivar, plant density and type of spray equipment), edaphic and (micro)climatological aspects may differ in such a way that comparisons between these experiments are difficult to make. The starting point in the present study is the literature on field experiments from which the interception fraction can be derived, directly or indirectly. The advantage of field trials is that they generally approach the typical agricultural practices by farmers the most closely. Greenhouse experiments on pesticide interception often differ from field experiments in their agronomic set-up, as they generally focus on plant- rather than crop-specific processes. On the other hand, greenhouse experiments generally show better material balances, as the occurrence of confounding variables (e.g., edaphic and (micro)climatological conditions) is more limited. Therefore greenhouse experiments are assumed to be less useful for indicating the range of interception fractions under field conditions, though they can be used to substantiate particular trends.

In conclusion, the simple starting point has been adopted in the present study that the interception fraction plus the soil deposition fraction is unity ($F_{\mathrm{int}} + F_{\mathrm{soil}} = 1$), unless other routes (e.g., via the air) are clearly indicated.

A list of acronyms and abbreviations used is given in Section 9.

2. CURRENT RISK ASSESSMENT APPROXIMATIONS

2.1 Northern and Central Europe

2.1.1 Arable crops

The Dutch decision-support system USES 2.0 characterizes environmental risks—with respect to, among others, groundwater leaching and hazards to terrestrial populations of agroecosystems—by taking standard crop-specific interception fractions into account (see Table 1) [5].

These fractions are a rough summary of the crop-specific fractions as assessed by a committee of Dutch experts evaluating the Multi-Year Crop Protection Plan [6]. This committee assessed the crop-specific soil deposition fractions (F_{soil}) as the starting point, rather than simultaneously assessing the crop interception, the soil deposition, and the emission to the air. The committee also specified the period of the year rather than a particular growth phase.

The German proposals for interception fractions have been published by Becker *et al.* [4]. See for additional information on the growth phases in Section 4.

2.1.2 Flower bulbs

There are no specific standard interception fractions in the Netherlands for the environmental risk assessment following pesticide use for bulb cultivation, nor have they been found in the literature assessed.

2.1.3 Orchards

In Table 2, the standard interception factors are given as used for fruit trees in The Netherlands.

2.1.4 Other crops

In Table 3, the standard interception factors are given as used for grassland in The Netherlands.

For pesticide registration purposes, in the Netherlands 0.1 and 0.8 are used as general default interception and soil deposition fractions, respectively, in case no standard fractions are available, or in case it is not clear on which growth phase of the crop, the pesticide is intended to be used. This option reflects a worst-case scenario.

Table 1 Interception fractions for the shoot (F_{int}) and soil deposition fractions soil (F_{soil}) for arable crops in various countries in use for risk assessment ($0 \le F_{int}$ or F_{soil} or $F_{air} \le 1$). In the Netherlands, F_{soil} is actually the standard fraction of the dosage reaching the soil assuming a crop-specific F_{int} and a default fraction of the dosage to the air of 0.1. A.e. is after emergence.

Arable crop	Country	Growth phase	F_{int}	F_{soil}	Reference
Potatoes I	The Netherlands	2–4 weeks a.e.	0.2	0.7	5
Potatoes II	The Netherlands	full growth	0.8	0.1	5
Potatoes I	Germany	Leaf development (*BBCH 10-19*)	0.15		4
Potatoes II	Germany	Formation basal side shoots/main stem elongation (*BBCH 20-39*)	0.45		4
Potatoes III	Germany	Inflorescence emergence/ripening (*BBCH 50-89*)	0.80		4
Potatoes IV	Germany	Senescence (*BBCH 90-99*)	0.50		4
Beets I	The Netherlands	2–4 weeks a.e.	0.2	0.7	5
Beets II	The Netherlands	full growth	0.8	0.1	5
Beets I	Germany	Leaf development (*BBCH 10-19*)	0.2		4
Beets II	Germany	Rosette growth (*BBCH 30-39*)	0.7		4
Beets III	Germany	Development of vegetative plant parts/senescence (*BBCH>40*)	0.9		4
Peas I	The Netherlands	short a.e.	0.1	0.8	5
Peas II	The Netherlands	around bloom	0.7	0.2	5
Peas I	Germany	Leaf development (*BBCH 10-19*)	0.35		4
Peas II	Germany	Formation of side shoots/stem elongation (*BBCH 30-59*)	0.55		4
Peas III	Germany	Inflorescence emergence/ripening (*BBCH 60-89*)	0.85		4
Rape I	Germany	Leaf development (*BBCH 10-19*)	0.4		4
Rape II	Germany	Formation of side shoots/stem elongation (*BBCH 50-89*)	0.8		4
Rape III	Germany	Inflorescence emergence/ripening (*BBCH 50-99*)	0.9		4
Maize I	Germany	Leaf development (*BBCH 10-19*)	0.25		4
Maize II	Germany	Stem elongation (*BBCH 30-39*)	0.50		4
Maize III	Germany	Inflorescence emergence/flowering (*BBCH 50-69*)	0.75		4
Maize IV	Germany	Development of fruit/ripening (*BBCH 70-89*)	0.90		4
Cereals I	The Netherlands	one month a.e.	0.1	0.8	5
Cereals II	The Netherlands	full growth	0.8	0.1	5
Cereals I	Germany	Leaf development (*BBCH 10-19*)	0.25		4
Cereals II	Germany	tillering (*BBCH 20-29*)	0.5		4
Cereals III	Germany	Stem elongation (*BBCH 30-39*)	0.7		4
Cereals IV	Germany	Booting/senescence (*BBCH 40-99*)	0.9		4
Sprouts I	The Netherlands	full growth	0.7	0.2	5
Onion I	The Netherlands	full growth	0.5	0.4	5

2.1.5 Scenario development in the European Union

In the procedure of the European Union to place plant protection products on the market as described in the EU-Directive 91/414/EEC, it is stated that the estimation of concentration in environmental compartments should be carried out using an appropriate model validated on community level. To be able to do so, an inventory of mathematical models was carried out, and in the next step European scenarios

Table 2 Standard interception fractions (F_{int}) for fruit trees in the Netherlands [5].

Arable crop	Growing phase	F_{int}	F_{soil}	F_{air}	Reference
Apple I	in spring	0.4	0.5	0.1	5
Apple II	full foliage	0.7	0.2	0.1	5

Table 3 Standard interception fractions (F_{int}) for grassland in the Netherlands [5].

Grassland	Growing phase	F_{int}	F_{soil}	F_{air}	Reference
Grassland		0.4	0.5	0.1	5

Table 4 Interception (%) by apples, bushberries, citrus, and vines depending on growth phase.

Crop	Growth phase			
Apples	without leaves, 50	Flowering, 65	Foliage development, 70	Full foliage, 80
Bushberries	without leaves, 50	Flowering, 65	Flowering, 65	Full foliage, 80
Citrus		all phases, 70		
Vines	without leaves, 40	Leaf development, 50	Flowering, 70	Ripening, 85

Table 5 Interception (%) by crops depending on growth phase.

Crop phase BBCH	Bare—emergence 00–09	Leaf development 10–19	Stem elongation 20–39	Flowering 40–89	Senescence, Ripening 90–99
Beans (field + vegetable)	0	0 25	40	70	80
Cabbage	0	25	40	70	90
Carrots	0	25	60	80	80
Cotton	0	10	20	40	25
Grass	90	90	90	90	90
Linseed	0	30	60	70	90
Maize	0	25	50	75	90
Oilseed rape	0	40	80	80	90
Onions	0	10	25	40	60
Peas	0	35	55	85	85
Potatoes	0	15	50	80	50
Soybean	0	35	55	85	65
Cereals	0	25	50 (tillering)	70 (elong.)	90
Strawberries	0	30	50	60	60
Sugar beets	0	20	70 (rosette)	90	90
Sunflower	0	20	50	75	90
Tobacco	0	50	70	90	90
Tomatoes	0	50	70	80	50

were established using the models selected in the earlier step. Estimation of the foliar interception was also part of the input value determination for the models. In the report of the working group [7] the following approach (Tables 4 and 5) was adopted, based on Becker *et al.* [4] and Van de Zande *et al.* [8].

2.2 United States of America

In the United States, the U.S. EPA Office of Pesticide Programs (OPP) uses data on application of pesticides to the foliage of both target crops and other nontarget plants and on dissipation of the chemical from that foliage in ecological and in human health risk assessments carried out for registration and reregistration of pesticide under the Federal Insecticide Fungicide Rodenticide Act (FIFRA) and the Food Quality Protection Act (FQPA). These assessments are primarily carried out by two divisions within OPP: the Environmental Fate and Effects Division (EFED) and the Health Effects Division (HED).

The Environmental Fate and Effects Division calculates pesticide estimated environmental concentrations (EECs) in surface water and in potential avian and mammalian food items for ecological risk assessments under FIFRA. The estimated concentrations are compared to toxicological measurements to assess potential risk. EFED also estimates concentrations in surface and ground water for human health risk assessments under FQPA. These exposure assessments are primarily carried out using the PRZM and EXAMS computer models and simpler screening models. Foliar application, wash-off, and degradation are an important component of this modeling.

The Health Effects Division (HED) estimates risk to human health and life both to agricultural workers through direct exposure on the job as well as to the population at large through ingestion of agricultural products on which pesticide residues may remain. Foliar application and residues are of interest in both types of assessments. Rates of dissipation of pesticide on foliage are of direct interest in establishing re-entry periods for workers after a field application. These tests and the re-entry periods set are needed to reduce worker exposure to a minimum. Foliar dissipation rates are also important in understanding residues on foliar crops such as spinach and the lettuces.

The Pesticide Root Zone Model (PRZM3), now in version 3.12, has the capability to simulate pesticide application to crop foliage as well as volatilization from the foliage, degradation on the foliage, and wash-off from the foliage. Pesticide, which is washed off the foliage, is treated by the program as a new application to the soil. The program assumes that the fraction of an application that is deposited directly on the foliage is the same as the fraction of the soil, which has foliage directly above it on the application day. The remainder is deposited directly to the soil. The program also assumes that the crop foliage increases in aerial extent from zero on the date of crop emergence (EMD) to a maximum (COVMAX) on the date of crop maturity (MAD). For most crops, this maximum coverage will be in the order of 80 to 100%. See Table 6 for recommended values. The increase in foliar cover may be linear or nonlinear (exponential).

In addition to the modeling approach presented above, an empirical approach for the estimation of maximum pesticide residue levels resulting from initial interception by various plant components has been used in the United States for some time. The basis for this approach was an industry need in the early 1970s for exposure estimates to support initial toxicological assessments of pesticides for nontarget terrestrial organisms (e.g., birds, wild mammals). By use of foliar pesticide data from 22 published field studies (21 pesticides), which represented more than 250 different pesticide–crop combinations, a correlation analysis of pesticide application rate vs. initial concentration for seven plant categories was developed by Eugene Kenaga of the Dow Chemical Agricultural Products Department [9]. Both “upper limit” values, which encompassed greater than 95% of reported values, and “typical limit” values, which represented the means of reported values, were developed (Table 7). During the early 1980s, the need for regulatory assessments of pesticide exposure led the U.S. Environmental Protection Agency (USEPA) to transform this analysis into an easily used nomogram to be used as part of the standard operating procedures for risk assessment [10]. Use of the so-called Kenaga nomogram allows estimation of pesticide concentrations in plant foliage based on plant type and application rate, and its international applicability was previously reviewed by IUPAC [11]. Because the Kenaga nomogram was based on data developed during the 1960s and early 1970s, during which time some older pesticide products were used which have been subsequently replaced (e.g., DDT, aldrin, endrin), a reassessment of its accuracy has been recently completed [12]. Results of this analysis of field residue data from 249 published papers representing 121 different pesticides and 118 different plant species largely confirmed the accuracy and conservative nature of the earlier estimations (Table 7). Only the maximum estimates for forage crops and fruits were found to be exceeded with enough frequency, 22% and 19%, respectively, so as to merit upward adjustment for a worst-case assessment.

Strengths of the Kenaga nomogram approach include its ease of use, long-term use and widespread acceptance, provision of foliar interception values in units of mg/kg, and inclusion of both crop and non-crop plants. Its main utility has been in support of worst-case, early-tier assessments of terrestrial nontarget organism dietary intake. The conservative nature of the estimates it yields stems in part from the fact that mechanisms by which pesticide residues decrease in plants (e.g., growth dilution, degradation, volatility, wash-off) are not considered. In addition to these factors, both crop- and pesticide-specific parameters would be required for more refined assessments. Employment of this more highly refined approach for specific chemicals and crops has highlighted the highly conservative nature

Table 6 Values of maximal coverage of the soil: COVMAX.

Crop	COVMAX
Alfalfa hay	100
Apples	90
Barley	100
Corn	100
Cotton	80
Grapefruit	70
Grass-hay	100
Lemons	70
Lettuce	80
Oats	100
Onions	70
Oranges	70
Pasture	98
Peanuts	100
Potatoes	90
Sorghum	99
Soybeans	100
Strawberries	85
Sugarcane	100
Sugar beets	70

Table 7 Estimated mean and maximum limits (in terms of mass fractions mg/kg = ppm) for initial pesticide residues on crop groups following application of 1 kg/ha[a].

Plant category	Estimated $\bar{w}$ (mg/kg) Hoerger & Kenaga [9]	Field data $\bar{w}$ ± S.D. (mg/kg) Fletcher *et al.* [12]	Estimated w_{max} (mg/kg) Hoerger & Kenaga [9]	Estimated w_{max} (mg/kg) Fletcher *et al.* [12]
Short-range grass	112	76 ± 54	214	214
Long grass	82	32 ± 36	98	98
Leaves, leafy crops	31	31 ± 40	112	112
Forage legumes	30	40 ± 51	52	121
Pods and seeds	3	4 ± 5	11	11
Fruits	1	5 ± 9	6	13

[a]Reported values in lb/a (pounds per acre) were transformed to values in kilograms per hectare where 1 lb/a = 1.12 kg/ha.

of the estimates provided by the Kenaga nomogram [13]. At present, the USEPA and industry are involved in the collaborative Ecological Committee on FIFRA Risk Assessment Methods (ECOFRAM) effort, which is targeted at developing more highly refined, probabilistic approaches to terrestrial nontarget organism risk assessment [14]. This work will include proposals for more advanced methods of estimation and measurement of nontarget organism risk, including that of foliar deposition rates of pesticides.

3. FIELD EXPERIMENTS

3.1 Northern and Central Europe

Field experiments are considered useful for indicating the range of interception fractions if they comply with the following requirements: (1) the cultivation system is comparable with current agronomic practice, (2) the growth phase of the crop is clearly reported, (3) the methodology is valid, and (4) the reporting is adequate. Aerial applications are not included for reasons of convenience. In general, interception fractions are expected to be lower for aerial applications than for applications from the ground [15].

A part of these interception data is based on the soil cover (i.e., the vertical projection of the crop on the soil) of various crops on control plots in numerous field trials in Northern and Central Europe [4]. These soil covers were pragmatically corrected for weed cover by calculating the mean of the soil cover for a particular growth phase *plus* one time the standard deviation, instead of the mean ± the standard deviation. This correction was confirmed by some actual field data. Therefore this approach seems to be promising.

Another part of the data in this section is directly derived from field trials in which the interception of pesticides has been measured by tracer or pesticide residue analysis of the crops. A third part of the data is indirectly derived from field trials in which the pesticide fraction that finally reaches the soil has been measured. As we are actually interested in the latter, we may subtract these fractions from 1 to obtain an estimated fraction, which is based on a real F_{soil}.

The field interception data in this chapter are lumped by crop-specific growth phase, irrespective of particular experimental conditions such as the meteorology, the type of sprayer, and the active ingredient. The underlying assumption is that the amount of leaves that cover the ground is primarily decisive for the actual interception fraction. This is also assumed by Jagers op Akkerhuis [3]. Various field data are included to indicate these experimental ranges of interception fractions by growth phase. It should be noted that crop interception is probably not linearly correlated with the soil cover by the crop in general, but with the plant biomass, as was demonstrated by Wauchope and Street [16] for rice. Therefore, linear interpolation of interception fractions in view of different soil covers is not reliable, but may be used as a best guess, if necessary.

Figures 1, 2, and 3 show the experimental ranges of interception fractions from field data respecting potatoes, sugar beets, and cereals, respectively. It is clear that these ranges—as they reflect different experimental conditions—may be large, especially for those growth phases in which the leaves are developing. However, these ranges appear to be larger for potatoes than for sugar beets and cereals, whereas for the latter, the later growth phases—stem elongation, senescence—have larger ranges.

Figure 3 shows that interception fraction estimates based on soil cover—corrected for the weed cover—may give less wider ranges, than when interception fractions are also based on other field data that actually assess the final pesticide depositions on soil (*cf* Fig. 4). These additional data from the field trials with cereals [8] include much lower interception fractions than those estimated by Becker *et al.* [4]. This may mean that the method of Becker *et al.* overestimates the actual interception fractions of cereals. However, the data of Becker *et al.* are more consistent, whereas the data of Van de Zande *et al.* reflect more different experimental set-ups. Therefore, the estimates by Becker *et al.* are probably more suitable for comparing the major growth phases within one crop.

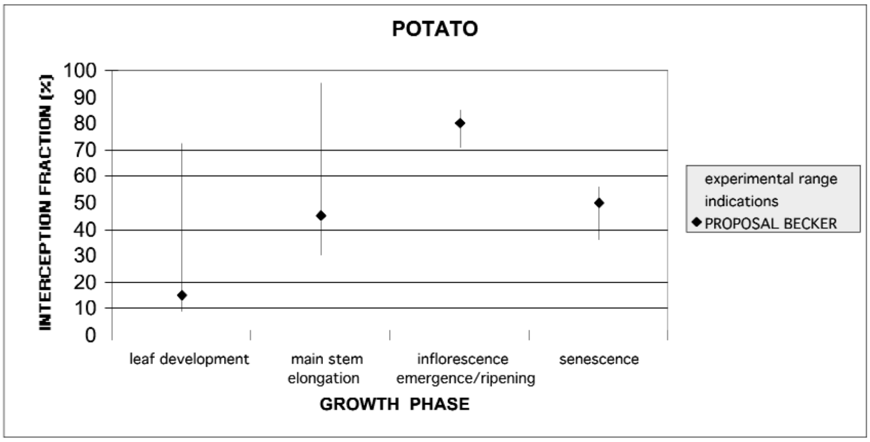

Fig. 1 The ranges for the interception fractions of potatoes derived from field trials [4,8].

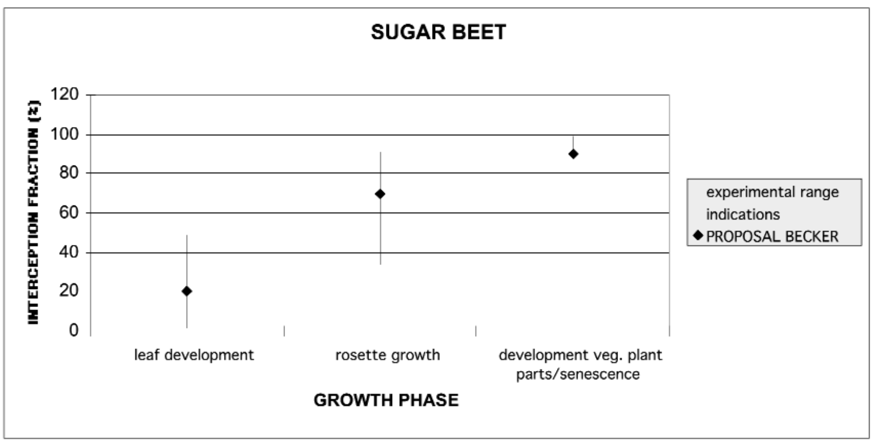

Fig. 2 The ranges for the interception fractions of sugar beets derived from field trials [4,8].

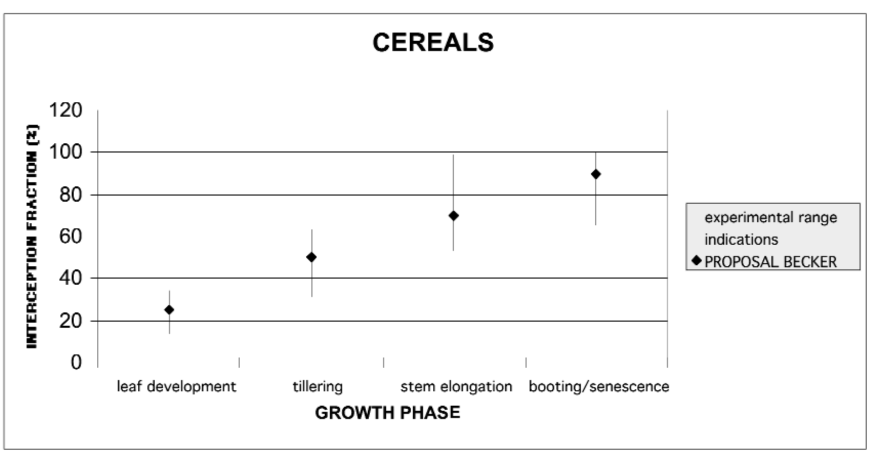

Fig. 3 The ranges for the interception fractions of cereals derived from field trials [4].

The interception fraction for the four-leaf phase of maize (*Zea mays*)—which is a sub phase within the growth phase of leaf development (see Fig. 5)—as estimated by Becker *et al.* [4] is confirmed by a greenhouse experiment of Wauchope *et al.* [2]. In this experiment, the total mass of the spray mixture intercepted by individual plants was measured by weighing the amount of spray liquid that was retained by the leaves, within a few minutes after application. The interception fraction thus determined was 7–13% of the nominal application rate, whereas the interception fraction for this growth phase of maize was estimated by Becker *et al.* to be 7–12%. In earlier experiments with the same growth phase of maize, Wauchope *et al.* found for chlorpyrifos much lower interception fractions, varying between 0.12 and 0.51%. However, this rapid loss from the leaves may, among others, have been due to some breakdown. The results of Wauchope *et al.* confirm—at least for one particular growth phase—that the estimation method by Becker *et al.* [4] is indeed promising.

Experimental ranges for the interception fractions in other crops such as oilseed rape, (fodder) peas, apples, and bulbs are represented in Figs. 6–9, respectively.

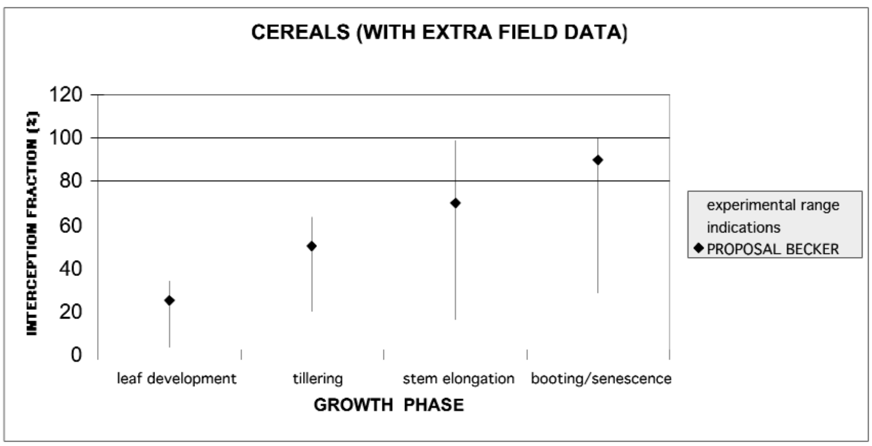

Fig. 4 The ranges for the interception fractions of cereals derived from field trials [4,8]. This figure contains all data from Fig. 3, and is extended with additional field data of Van de Zande *et al*. for which F_{int} is assumed to equal 100 minus F_{soil}.

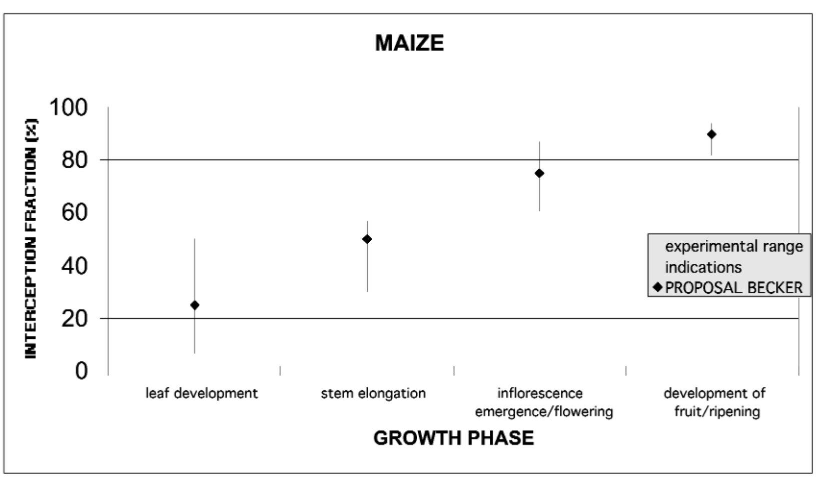

Fig. 5 The ranges for the interception fractions of maize (*Zea mays*) derived from field trials [4].

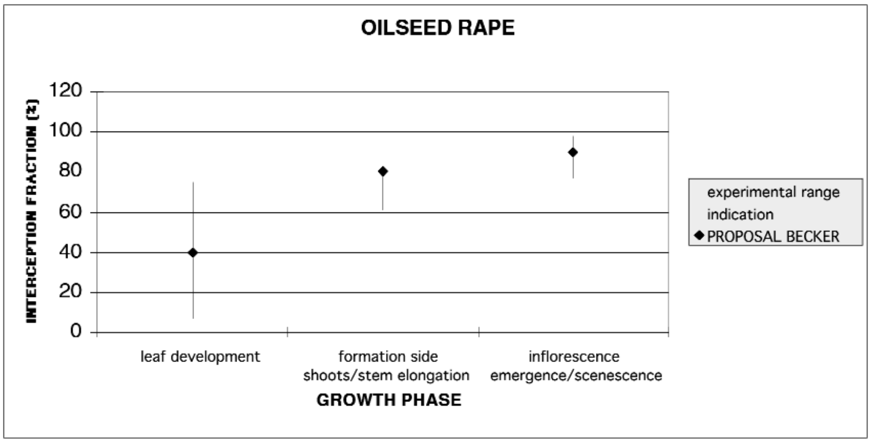

Fig. 6 The ranges for the interception fractions of oilseed rape derived from field trials [4].

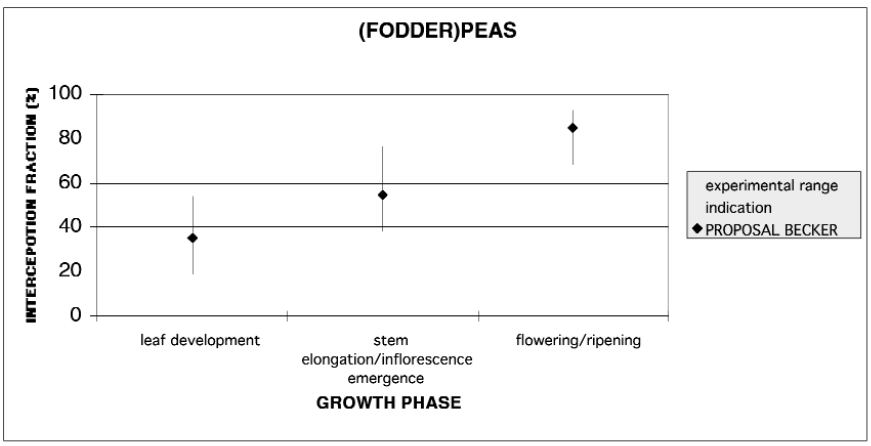

Fig. 7 The ranges for the interception fractions of (fodder) peas derived from field trials [4].

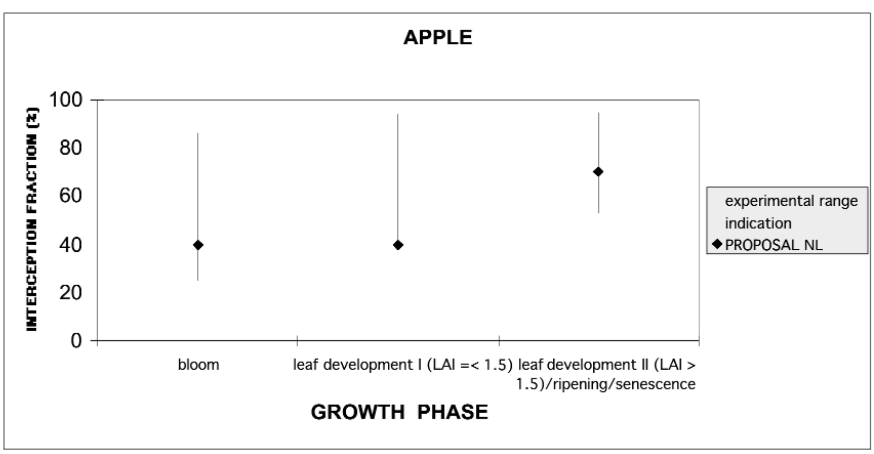

Fig. 8 The ranges for the interception fractions of apples derived from field trials [8].

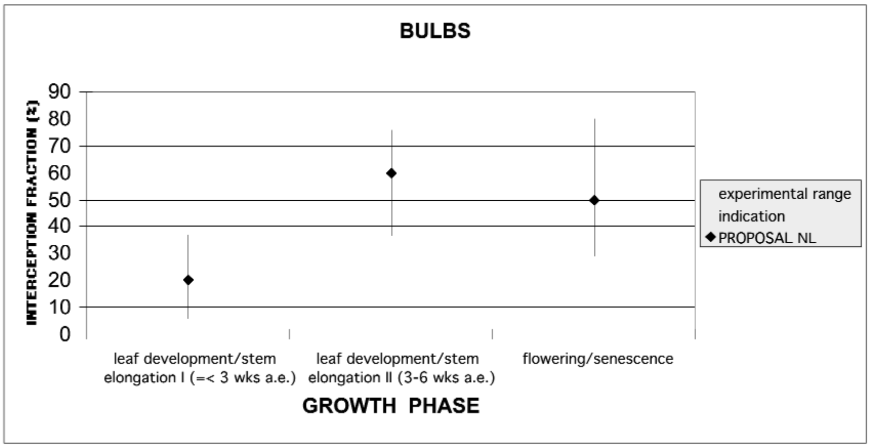

Fig. 9 The ranges for the interception fractions of bulbs derived from field trials [8].

The field data in Fig. 8 are primarily based on Dutch field trials. Therefore, typical Dutch cultivars—that generally bloom before the start of the leaf development—are taken into account. Of course, this can be quite different in other countries, and again this stresses the estimation character of the proposals for standard crop interception fractions.

The field data on the interception by apple trees show large differences within the growth phases. One may even doubt whether the actual differences between the major growth phases are statistically significant, as suggested by the Dutch proposal for the growth phases of bloom and leaf development I vs. leaf development II.

This clearly indicates the relativity of the use of standard growth phase- and crop-specific interception fractions. However, for most of the crops examined in this chapter, the proposed standard interception fractions reflect the trends that can be seen for the interception fractions directly or indirectly derived from field trials. The interception by apples appears to be an exception in this respect, as the proposals for the subsequent growth phases of bloom and leaf development I (see Fig. 8) are in the lower regions of the experimental ranges.

3.2 United States of America

Data from Willis *et al.* [17] may not be useful for deriving standard interception fractions for "immature" cotton, as there is no clear explanation for the difference between the interception fraction by the crop and the soil deposition fraction (as they do not equal unity, although residues were measured ≤3 h after application, see Table 8). Provisional estimates using the class ranges of cotton from Table 8 may be 0.2 for cotton with soil cover ≤50%, and 0.8 for cotton with a soil cover >50%. Provisional estimates using the class ranges of rice from Table 8 may be 0.3, 0.7, and 0.9 (as a max. F_{int}, as otherwise European models for soil leaching cannot be run) for the subsequent growth phases with soil covers ≤70%, 70–100% (immature), and 100% (mature). The interception fractions >1 may be due to analytical recoveries or actual application rates greater than assumed.

4. GROWTH PHASES

In 1997, the extended BBCH-scale was published in Germany by a joint publication of the Federal Biological Research Centre for Agriculture and Forestry (BBA), the Federal Office of Plant Varieties (BSA), the Federation of Agrochemical Industries (IVA) and the Institute for Vegetables and Ornamentals [23]. The extended BBCH-scale is a system for a uniform coding of phenologically sim-

Table 8 Interception and soil deposition fractions ($0 \le F_{int}$ or $F_{soil} \le 1$) in field trials with crops other than Northern or Central European.

Crop	Country	Growth phase	F_{int}	F_{soil}	Reference
Cotton 1	USA	0.5 m height; 45% soil cover; row spacing 1.02 m; LAI 0.7	0.19–0.28	0.09–0.55	17
Cotton 2	USA	mature; 75% soil cover	0.66–0.92	-	18
Cotton 3	USA	1.22 m height; 100% soil cover; row spacing 1 m	0.39–1.27	-	19
Cotton 4	USA	mature; 1.22 m height; 100% soil cover; row spacing 1 m	0.9–1.14	-	20
Cotton 5	USA	mature; 100% soil cover; row spacing 1 m	0.44–1.11	-	21
Cotton 6	USA	Mature; LAI c. 2.8	0.54–0.68	-	22
Rice 1	USA	61% soil cover; row spacing 0.3 m	0.33	-	16
Rice 2	USA	100% soil cover; height 0.8 m; row spacing 0.3 m	0.66	-	16
Rice 3	USA	100% soil cover; mature; height 1.3 m; row spacing 0.3 m	1.27	-	16

Table 9 Principal growth phases of BBCH.

Phase	Description
0	Germination/sprouting/bud development
1	Leaf development (main shoot)
2	Formation of side shoots/tillering
3	Stem elongation or rosette growth/shoot development (main shoot)
4	Development of harvestable vegetative plant parts or vegetatively propagated organs/booting (main shoot)
5	Inflorescence emergence (main shoot)/heading
6	Flowering (main shoot)
7	Development of fruit
8	Ripening or maturity of fruit and seed
9	Senescence, beginning of dormancy

ilar growth phases of all mono- and dicotyledonous plant species. The abbreviation BBCH stands for the Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie. The developmental cycle of the plants is subdivided into 10 recognizable and distinguishable longer-lasting developmental phases. The principal growth phases are described in Table 9. In the current paper the term “growth phases” is used instead of “growth stages”, as in the original document of BBA [23].

In addition, secondary phases are used if points of time or steps in the plant development must be indicated precisely. The BBCH-scale may also be used for plants not included in the original publication by giving the same code to similar phenologically identical phases compared to available data of the plants under consideration.

In the proposal for the estimation of the interception factors of plant protection products by the plants themselves a relation is assumed between the growth phase of the plant and the amount of interception. However, some exceptions to this rule will be indicated.

5. OTHER CONSIDERATIONS

The interception fraction may depend on various parameters: the droplet size, the type of sprayer (e.g., air-assisted vs. tunnel), the spray volume, the cultivation system (e.g., the type of crop cultivar, the crop density, and therefore the drilling pattern), the canopy structure, and (micro)climatological variables as wind direction and wind speed [2,4,15,24]. The droplet size and the spray volume may depend on the presence of viscosity-increasing agents, the adjusted pressure, the type of nozzles, and the driving speed. However, the impact of droplet size and spray volume on final interception fractions by the different crop strata is probably limited [3]. After being intercepted by the crop, pesticides may be retained by the leaves and stem until they are, for example, dissipated to the soil via dripping or degraded. The extent of retention by the leaves and stem may depend on the chemical and physical properties of the active ingredient (e.g., volatility), the chemical and physical properties of adjuvants in the formulation, the air and leaf temperature, the leaf ankle, the pattern of leaf venation, and the structure and composition of wax or the occurrence of trichomes. Spray droplets may also directly bounce from reflective leaf surfaces, although for herbicides this may be prevented by adding surfactants [25].

The present study focuses on interception rather than on retention. Conceptually, it is assumed that both interception and deposition on soil are instantaneous processes. This is, of course, an oversimplification. Retention by the crop may imply losses via different routes (e.g., via transformation or volatilization) while on the leaf. It may also imply soil deposition spread out over a longer period of time, with possible consequences for the extent and duration of exposure for terrestrial organisms. Experiments indicate that foliar wash-off due to rainfall can be substantial: Willis *et al.* [26] showed that the first 2 to 3 mm of rain after a pesticide application removed 50% of the total amounts of the insecticides permethrin and sulprofos from mature cotton plants by a 51-mm rain storm. In the present study, retention fractions are seen as minimal interception fractions, as the extent of retention can never exceed the extent of interception.

6. PROPOSAL FOR HARMONIZED INTERCEPTION FACTORS

Taking into account the information available in the literature that has been presented, a proposal for harmonized interception factors has been derived. Table 10 gives the proposed value for a variety of crops. It should be stressed that many crops are not listed in Table 10. However, referring to common growth phases with other, similar crops an estimation of the interception values for other crops may be possible. Expert judgement should be guiding in those cases. The interception values are generally related to the growth phases as defined in the BBCH-scale. For some crops this was not possible, and therefore a deviating indication has been used to describe the growth situation. The abbreviation LAI stands for Leaf Area Index.

Table 10 Proposal for crop and growth phase-specific interception fractions (F_{int}) for crops.

Crop	Growth phase	BBCH-code or LAI	F_{int}
Bare soil - Pre-emergence	Not applicable	-	0.00
Beans I	Leaf development	10–19	0.25
Beans II	Stem elongation	20–39	0.40
Beans III	Flowering	40–89	0.70
Beans IV	Ripening/senescence	90–99	0.80
Bulbs I	Leaf development/stem elongation I (≤3 weeks a.e.)	-	0.20
Bulbs II	Leaf development/stem elongation II (3–6 weeks a.e.)	-	0.60
Bulbs III	Flowering/senescence	-	0.50
Cabbage I	Leaf development	10–19	0.25
Cabbage II	Development of harvestable plant parts	40–49	0.80
Cabbage III	Flowering	50–89	0.90
Cabbage IV	Ripening/senescence	90–99	0.90
Carrots I	Development of leafs and harvestable plant parts	10–49	0.25

(*Continued on next page*)

Table 10 (*Continued*)

Crop	Growth phase	BBCH-code or LAI	F_{int}
Carrots II	Inflorescence emergence/flowering	50–69	0.50
Carrots III	Development of fruits	70–79	0.70
Carrots IV	Ripening/senescence	80–99	0.60
Cereals I	Leaf development	10–19	0.25
Cereals II	Tillering	20–29	0.50
Cereals III	Stem elongation	30–39	0.70
Cereals IV	Booting/senescence	40–99	0.90
Citrus I	Leaf and shoot development	10–39	0.30
Citrus II	Inflorescence emergence	50–59	0.50
Citrus III	Flowering/development of fruit/maturity	60–89	0.70
Citrus IV	Senescence	90–99	0.70
Cotton I	Leaf development	10–19	0.25
Cotton II	Side shoots	20–29	0.60
Cotton III	Stem elongation/crop cover/flowering	30–89	0.70
Cotton IV	Senescence	90–99	0.90
Currants I	Leaf development	10–19	0.30
Currants II	Shoot development/inflorescence emergence	20–59	0.40
Currants III	Flowering/development of fruit/maturity	60–89	0.60
Currants IV	Senescence	90–99	0.60
Grass I	All phases	-	0.40
Hops I	Leaf development	10–19	0.20
Hops II	Side shoots/elongation of bines	20–39	0.60
Hops III	Inflorescence emergence/maturity	50–89	0.90
Hops IV	Senescence	90–99	0.50
Linseed I	Leaf development	10–19	0.20
Linseed II	Stem elongation	20–39	0.60
Linseed III	Flowering/ripening	40–89	0.70
Linseed IV	Senescence	90–99	0.90
Maize I	Leaf development	10–19	0.25
Maize II	Stem elongation	30–39	0.50
Maize III	Inflorescence emergence/flowering	50–69	0.75
Maize IV	Development of fruit/ripening	70–99	0.90
Oilseed rape I	Leaf development	10–19	0.40
Oilseed rape II	Formation of side shoots/stem elongation	20–39	0.80
Oilseed rape III	Inflorescence emergence/ripening/senescence	50–99	0.90
Onions I	Leaf development	10–19	0.10
Onions II	Stem elongation	20–39	0.25
Onions III	Flowering	40–89	0.40
Onions IV	Ripening/senescence	90–99	0.60
Peas I	Leaf development	10–19	0.35
Peas II	Stem elongation/inflorescence emergence	30–59	0.55
Peas III	Flowering/ripening	60–89	0.85
Olives I	Leaf and shoot development	10–39	0.30
Olives II	Inflorescence emergence	50–59	0.50
Olives III	Flowering/development of fruit/maturity	60–89	0.70
Olives IV	Senescence	90–99	0.70
Pome fruit I	Without leaves	-	0.20
Pome fruit II	Bloom/leaf development I	(LAI ≤ 1.5)	0.40
Pome fruit III	Leaf development II	(LAI > 1.5)	0.70

(*Continued on next page*)

Table 10 (*Continued*)

Crop	Growth phase	BBCH-code or LAI	F_{int}
Pome fruit IV	Full foliage	-	0.80
Potatoes I	Leaf development	10–19	0.15
Potatoes II	Formation basal side shoots/main stem elongation	20–39	0.50
Potatoes III	Inflorescence emergence/ripening	50–89	0.80
Potatoes IV	Senescence	90–99	0.50
Rice I	Leaf development	10–19	0.20
Rice II	Booting, inflorescence emergence	20–59	0.50
Rice III	Flowering, fruit development	60–79	0.70
Rice IV	Ripening, senescence	80–99	0.90
Soybean I	Development of leaf /harvestable plant parts	10–19	0.20
Soybean II	Side shoots and development of harvestable plant parts	20–49	0.60
Soybean III	Inflorescence/senescence	50–99	0.90
Sprouts I	Leaf development	10–19	0.20
Sprouts II	Side shoots/rosette growth	20–49	0.50
Sprouts III	Inflorescence/flowering	50–89	0.80
Sprouts IV	Fruit development/ripening	90–99	0.70
Stone fruit I	Without leaves	-	0.20
Stone fruit II	Bloom/leaf development I	(LAI ≤ 1.5)	0.40
Stone fruit III	Leaf development II	(LAI > 1.5)	0.70
Stone fruit IV	Full foliage	-	0.80
Strawberries I	Leaf development	10–19	0.30
Strawberries II	Development of stolons and young plant parts	40–49	0.50
Strawberries III	Inflorescence emergence–maturity	50–89	0.70
Strawberries IV	Senescence/dormancy	90–99	0.60
Sugar beets I	Leaf development	10–19	0.20
Sugar beets II	Rosette growth	30–39	0.70
Sugar beets III	Development of vegetative plant parts/senescence	>40	0.90
Sunflower I	Leaf development/stem elongation	10–39	0.40
Sunflower II	Inflorescence emergence	50–59	0.70
Sunflower III	Flowering/ripening	60–89	0.90
Sunflower IV	Senescence	90–99	0.80
Tobacco I	Transplant	-	0.10
Tobacco II	Layby	-	0.60
Tobacco III	Full flower	-	0.80
Tobacco IV	Mature topped	-	0.90
Tomatoes I	Leaf development	10–19	0.25
Tomatoes II	Side shoots/inflorescence emergence	20–59	0.50
Tomatoes III	Flowering/fruit development/ripening	60–89	0.70
Tomatoes IV	Senescence	90–99	0.60
Vines I	Leaf development	10–19	0.30
Vines II	Inflorescence emergence	50–59	0.50
Vines III	Flowering/development of fruit/ripening	60–89	0.80
Vines IV	Senescence	90–99	0.60

7. CONCLUSIONS AND DISCUSSION

Proposals for standard growth phase-specific interception fractions per crop are presented in Table 10. Most of these proposals are based on interception fractions that have been indirectly derived from the control plots of numerous efficacy field trials of BASF with herbicides for Northern and Central European crops. Therefore, most underlying data are based on the soil cover of a particular growth phase, and not on actual measurements of crop interception or soil deposition. It should be noted, however, that there has been a pragmatic correction for the weed cover in these control plots. Arguments in favour of this relatively simple approach of Becker *et al.* [4] are:

- the rapid acquirement of interception fractions, that otherwise would have to be obtained by technically complicated, elaborate, and expensive experiments;
- the estimates reflect the phenological development of a crop in time by taking all major growth phases into account; and
- there is a reasonable agreement between this approach and at least some of the few studies in which actual interception measurements have been performed (but not for all, see ref. 3).

On the other hand, the approach by Becker *et al.* inherently is an oversimplification of the complex processes that ultimately result in the actual crop interception and soil deposition of pesticides (*cf* Nordbo *et al.* [27] and Jagers op Akkerhuis *et al.* [3]). Important details of these processes are only recently under investigation, as was shown by Wauchope *et al.* [2] and Jagers op Akkerhuis *et al.* [3]. Model simulation (e.g., for cereals) has to be based on the intercepting surfaces of both leaves, stems, and ears, as all these parts contribute significantly to the interception fraction [3]. However, many relevant input parameters for such sophisticated simulation models will not always be available: for example, crop-stratified measurements on the number and mean area of stems, leaves, and ears. The results of more complicated modeling can be different from the results of the German approach, again indicating the relativity of the latter. Jagers op Akkerhuis *et al.* [3] found F_{soil} values for two growth phases of spring barley of 0.3 and 0.2 (both phases within the major growth phase of booting up to senescence, *cf* Figs. 3 and 4), whereas the F_{soil} according to the approach of Becker *et al.* is 1–0.9 = 0.1. The German approach in this particular case apparently underestimates the "actual" soil deposition, however, differences in crop density, fertilization, and varietal appearance could also be explanations as well.

The standardization of crop-specific interception fractions will be of great help for the environmental risk assessment of the soil and its inhabitants, especially at the first tier. However, in view of the preceding, it is tedious to derive such standardized values from analytical experiments for various reasons. First, there are not many experimental data available on this issue that are useful. Secondly, if experimental data are available, they are generally difficult to compare, as they differ in their experimental set-up and the edaphic and climatological factors. As an alternative, the approach by Becker *et al.* seems promising, although both over- and underestimation of the interception fraction may occur, as is demonstrated in the preceding text. This may have consequences for the type of risk assessment (e.g., whether to assess the risks in accordance with a worst-case scenario). Also, the "validation" of the interception fractions—as estimated by Becker *et al.*—by experimental measurements on the actual interception remains necessary, especially in view of the lack of useful experimental data on this issue in general.

The approach of Becker *et al.* fits with a proposal of the Danish EPA for estimating interception fractions [24]. This proposal was based on the extent of light interception by the different growth phases of crops by assuming: F_{soil} = [100] minus [95% of the soil cover by the crop]. Comparison of some of the field trials with actual measurements of F_{int} or F_{soil} shows for sugar beets, onions, and lilies that this Danish approach may both over- or underestimate the actual F_{soil} or F_{int}.

The experimental field data on which the proposals for standard interception fractions have been based are mainly from Northern and Central European crops. Data on, for instance, Mediterranean or subtropical crops are almost lacking. However, to some extent, some of such crops could possibly be compared with Northern or Central European crops, assuming that the interception data are based on comparable physical processes and comparable agronomic conditions (e.g., type of cultivation including plant densities). It is an additional advantage that the approach of Becker *et al.* assumes an indirect relation between the soil cover of the crop and the interception fraction: the interception fraction is the mean soil coverage fraction *plus* one time the standard deviation of the soil coverage fraction. The same approach could be applied for other crops. As an example: soybeans could be compared with (fodder) peas. However, as the leaf hairs of soybeans are the primary points of contact with the droplets, the contribution of bouncing droplets to the fraction that passes the vegetation (almost) immediately may be much larger than for the smooth, reflective surfaces of peas. In conclusion, it is recommended to extend the approach of Becker *et al.* to the crops outside Northern and Central Europe, knowing that data on soil cover by crops as determined in efficacy field trials may have been obtained already by agrochemical concerns. However, as there appears to be only few experimental data on the actual interception by these crops—as for the Northern and Central European crops—there remains a need for confirmation of these standard interception fractions by field trials.

8. RECOMMENDATIONS

1. A prerequisite assumption in performing risk assessments for plant protection products is that the product will be applied in accordance with **good agricultural practice**.
2. A few studies on foliar interception and retention are reported in the literature, and thus far, there has not been enough research to facilitate accurate estimates of spray interception for a large number of crops under the growing conditions in various parts of the world. The available literature seems therefore inadequate for a risk assessment in all cases. This is especially true with respect to field studies. However, some estimations have been reported which are based on expert judgement. It is recommended that **available literature on foliar interception and retention as summarized here be used in the first tier of the risk assessment** carried out for the registration of pesticides whenever reliable data exists.
3. Where suggested estimates could lead to inaccurate conclusions regarding risk, **additional (field) data** should be generated to carry out more realistic or accurate risk assessments for the product under consideration.
4. As the global distribution of the available data is rather limited, additional field data should be generated and **for as many different crops as possible in different geographical areas.**
5. The number of different crops for which field studies have been carried out is still limited. When performing risk assessments for a crop not mentioned, the most **appropriate values should be used from the table presented based on expert judgement.** However, for some crops the data may not be suitable for a first tier estimate of the interception or retention to use in the risk assessment. In this case, additional data are required to be generated on the interception and retention phenomena.
6. Surfactants used as adjuvants and other individual adjuvants may influence the interception and retention or rainfast properties of various pesticide sprays. The most **appropriate correction should be used taking into account the effects of the surfactants** based on expert judgement. Estimates of interception or retention should reflect the known effects of the specific adjuvants involved.
7. As the application equipment may influence the interception and/or retention, then the risk assessment should be based on **realistic estimates of the characteristics of the equipment** being used in a particular crop.
8. For **higher tier risk assessments**, it is necessary to obtain data from **field studies** to accurately characterize the foliar interception and/or the retention factors.

9. LIST OF ACRONYMS AND ABBREVIATIONS

a	acre
BBA	Biologische Bundesanstalt fuer Land- und Forstwirtschaft (Federal Biological Research Centre for Agriculture and Forestry)

BBCH	Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie (Federal Biological Research Center, Federal Office of Plant Varieties and Chemical Industry)
BSA	Bundessortenamt (Federal Office of Plant Varieties)
COVMAX	maximal coverage of soil area
ECOFRAM	Ecological Committee on FIFRA Risk Assessment Methods
EEC	European Economic Community, now European Union
EFED	Environmental Fate and Effects Division
EMD	emergence date
EU	European Union
EXAMS	Exposure Assessment Modelling System
F	Fraction of active substance [-]
FIFRA	Federal Insecticide Fungicide Rodenticide Act
FQPA	Food Quality Protection Act
ha	hectare
HED	Health Effects Division
int	as subscript: interception
IUPAC	International Union of Pure and Applied Chemistry
IVA	Industrie Verein fuer die Agrochemie (Federation of Agrochemical Industries)
kg	kilogram
LAI	leaf area index
lb	pound
MAD	maturity date
OECD	Organization for Economic Cooperation and Development
OPP	Office of Pesticide Programs
ppm	parts per million
PRZM	Pesticide Root Zone Model
RIVM	Rijksinstituut voor Volksgezondheid en het Milieu (National Institute for Public Health and the Environment)
USA	United States of America
USEPA	United States Environmental Protection Agency
USES	Uniform System for the Evaluation of Substances, decision-support system used in The Netherlands
VROM	Ministerie voor Volkshuisvesting, Ruimtelijke Ordening en Milieu (Ministry for Public Housing, Spatial Planning, and the Environment)
VWS	Ministerie voor Volksgezondheid, Welzijn en Sport (Ministry for Public Health, Welfare, and Sport)
w	mass fraction (mg/kg)

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