Sugar concentration in nectar: a quantitative metric of crop attractiveness for refined pollinator risk assessments

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Abstract

Those involved with pollinator risk assessment know that agricultural crops vary in attractiveness to bees. Intuitively, this means that exposure to agricultural pesticides is likely greatest for attractive plants and lowest for unattractive plants. While crop attractiveness in the risk assessment process has been qualitatively remarked on by some authorities, absent is direction on how to refine the process with quantitative metrics of attractiveness. At a high level, attractiveness of crops to bees appears to depend on several key variables, including but not limited to: floral, olfactory, visual and tactile cues; seasonal availability; physical and behavioral characteristics of the bee; plant and nectar rewards. Notwithstanding the complexities and interactions among these variables, sugar content in nectar stands out as a suitable quantitative metric by which to refine pollinator risk assessments for attractiveness. Provided herein is a proposed way to use sugar nectar concentration to adjust the exposure parameter (with what is called a crop attractiveness factor) in the calculation of risk quotients in order to derive crop-specific tier I assessments. This Perspective is meant to invite discussion on incorporating such changes in the risk assessment process.

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Keywords: pollinators; risk assessment; exposure; pesticides; crops; attractiveness; nectar

1 INTRODUCTION

All chemicals, anthropogenic and natural alike, have the potential to cause adverse effects. However, the likelihood and magnitude of an adverse effect (i.e. risk) depend on the receptor being exposed, the toxicity of the chemical and the route and duration by which exposure occurs. If all three of these variables overlap temporally and spatially, the possibility of risk after chemical exposure exists. Conversely, if one or more of these three variables is absent, then the probability of risk is negligible.

This interaction among receptor, toxicity and exposure is the fundamental principle upon which ecological risk assessments are based. It is also the base for European Food Safety Authority (EFSA), 1 United States Environmental Protection Agency (USEPA), Health Canada Pest Management Regulatory Agency (PMRA) and California Department of Pesticide Regulation (CalDPR) guidance 2 for assessing pollinator risk from exposure to pesticides. Aside from some differences in terminology (e.g. EFSA ‘predicted environmental concentration, or PEC’ is analogous to USEPA ‘estimated environmental concentrations, or EEC’; EFSA ‘plant protection products, or PPP’ are the same as USEPA ‘pesticides’) and technical approach (e.g. inclusion of different bee species), the processes are similar. In both cases the risk assessment process starts with a conservative screening level step (tier I) where modeled environmental concentrations are compared with laboratory-derived toxicity values (TRV) (e.g. contact and oral LD50 values) to make characterizations of risk against a regulatory acceptable threshold (i.e. EFSA ‘threshold trigger value’; USEPA ‘level of concern, or LOC’).

Based on the outcome of this tier, higher-tiered approaches with greater reliance on semi-field- (tier II) and field- (tier III) derived data are applied to make more refined risk characterizations.

Both the EFSA and USEPA acknowledge that exposure is a critical variable in the risk assessment process. For example, as stated by the EFSA, ‘ … PPP that was unlikely to come into any contact with bees during agricultural use would have a PEC of zero and the effect assessment component of the risk assessment process would be unnecessary’. 1 The USEPA stated: ‘ … If there is no exposure, then the likelihood of adverse effects (i.e., risk) is presumed to be low and an additional assessment is not warranted’. 2 These agencies also acknowledge that plant attractiveness to bees is directly related to exposure, meaning exposure of pollinators to agricultural pesticides is likely greatest for attractive plants and...
lowest for unattractive plants. Neither objective nor subjective
definitions of crop attractiveness to bees were provided by the
USEPA, but the EFSA and the United States Department of Agri-
culture (USDA) have recently compiled qualitative attractiveness
rankings of crops to honey bees (Apis mellifera), bumblebees (Bombus species) and solitary bees. In the EFSA approach, crops are con-
sidered attractive when there is evidence that bees collect nectar and/or pollen (indicated with a ‘+’ in their report). Attractiveness
was assessed as ‘low’, ‘crop is not visited by bees for nectar but
attractiveness for pollen cannot be excluded’ or ‘no information
available’. The USDA used a similar approach in their assessment of attractiveness (‘−−’ = not attractive; ‘++’ = attractive under certain
conditions; ‘+++’ = high attractiveness in all cases). According to
the USDA, the USEPA intends to use their crop attractiveness data
to assess exposure of bees to pesticides as part of the risk assess-
ment process.

What is missing from the EFSA and USEPA guidance documents,
however, is direction on how to modify the risk assessment process
given data about crop- and bee-specific variables that
actually drive plant attractiveness, and whether or not these vari-
cables can be used quantitatively to remark on attractiveness and
subsequent pesticide exposure of bees in the field. Accordingly,
presented herein is: (a) information about crop- and bee-specific
variables related to attractiveness; (b) identification of a key metric
that can be used quantitatively to predict attractiveness (with a
focus on ten crops grown in North America); and (c) the application
of this information to make suggested refinements to the risk
assessment paradigm.

2 CROP- AND BEE-SPECIFIC VARIABLES
RELATED TO ATTRACTIVENESS

A multifaceted approach was conducted to facilitate this study.
By entering combinations of keywords (e.g. pollinators, honey
bees, bumblebees, attractiveness, plants, crops) and study authors
flagged as ‘key influencers’ in the field into scientific and
general-purpose Internet search engines (Thomson Reuters Web of Science™ and Google Scholar respectively), information
about variables affecting general crop attractiveness to pollinators
was obtained from the peer-reviewed scientific literature and gray
literature.

No date restrictions were entered as part of the search, based
on the principle that science is cumulative, and by considering all
available evidence, the best science available would be reflected.
Discussions with, and input from, agricultural commodity groups
and pollinator experts were also used to inform this study. To assist
discourse, phrases such as ‘Do bees gather pollen and nectar from
crop?’ and ‘Is the crop a source of good nutrition?’ were given to
these groups and individuals.

It should be noted that studies retrieved from the scientific
databases and used to inform this paper did not undergo formal
inclusion and exclusion criteria, nor did the authors conduct a
critical review and critique of each source of information. Rather,
the literature cited herein was selected to illustrate an overall
knowledge of variables affecting general crop attractiveness to
pollinators. This paper is not intended to be a formal systematic
review of the scientific literature.

Searches in Web of Science™ and Google Scholar revealed a vast
body of literature on the topic. For example, in Web of Science™
the keyword combinations ‘plant × attractiveness × pollinators’
returned 314 results, ‘plant × attractiveness × bees’ returned 272
results and ‘crop × attractiveness × pollinators’ returned 72 results.

Searches in Google Scholar with the same keywords returned
between roughly 10,000 and 15,000 results. General phrases such
as ‘What makes crops attractive to bees?’ and ‘Why are crops
attractive to bees?’ returned even more (roughly 40,000 hits).

At a high level, the attractiveness of crops to bees appears
to depend on several key variables, including but not limited
to: floral morphology; olfactory, visual and tactile cues; seasonal
availability; behavioral and physical characteristics of the bee
and plant respectively; nectar rewards. Information about these
variables is provided in the following subsections.

2.1 Floral morphology and olfactory, visual and tactile cues

Plants can attract pollinators by flower size, color intensity, flower
number, accommodation of bee body size within the flower and
nectar production. External flower shape can also be an impor-
tant attractor. For example, Bombus spp. and A. mellifera prefer
segmented flowers with disrupted outlines; Bombus spp. may pre-
fer bilaterally symmetrical flowers more than A. mellifera. Bees
use visual, olfactory and tactile floral cues for recognition of,
and attraction to, floral sources. Visual cues such as flower color are
short-distance attractants, and at long distances the bees differen-
tiate color by background comparison.11 Flowers emit a bouquet of
odors, which act as long-distance attractants. There may be a
specific component to flower choice by a bee, especially for
specialist pollinators; for example, newly emerged females of Heriades truncorum seek a favorite flower (Asteraceae) despite feeding on
alternative pollens (Campanula L., Echium L. and Sinapis L.) dur-
ing larval development. In some plants, bees show a preference
for male traits rather than female traits. Recent research showed
that honey bees preferred the visual display (i.e. color) but not the
olfactory cues (plant volatiles) of male Salix caprea over that of
females. Other research indicates the opposite: it has been
suggested that the most important reason why honey bees alight
on a flower, even greater than forage quality, is the attraction
to pollen volatiles. Although color is not always a direct attractant
as many pollinators visit many flowers of many colors, plants have
used daily and seasonal flowering times to attract certain pollina-
tors through evolution.

2.2 Seasonal and daily availability

Other plants that are in bloom and within the foraging range of
the bees can significantly decrease the likelihood of forager visits to a
crop. Determinate or indeterminate flowering patterns likely
play a role in attractiveness. For example, a single cotton flower
opens at dawn, withers in the afternoon, closes by sunset and
never reblooms, thereby providing only morning nectar resources
for bees. The interplay of these variables also affects how bees
use a crop. For instance, crops with relatively low attractiveness
may still be, at certain times, an important source of food for bees.3
Also, honey bees are generalist and opportunistic pollinators,
which means, as the EFSA wrote, ‘even lowly attractive crops may
be abundantly visited by bees in certain circumstances (e.g. a few
varieties of flowering crops available in some area and/or in some
period of the year)’.

2.3 Physical and behavioral characteristics

Bees also differ in preference for flower height, time of
flower visitation and within-flower behavior, which seems related
to body size. Larger bees, which are able to forage earlier dur-
ing the cooler hours of the day, transport pollen, while smaller
bees foraging later in the day cause intraflower pollen transfer to
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The stigma. Competition has been observed among bee species, but it has not been quantitatively described. When it does occur, smaller bee species are generally observed to be subordinate.\(^2\)

Bee size is one of its own parameters that affect visitation; the plant creates its own strategy for attractiveness to bees by qualities such as flower size, color intensity, flower number and nectar production.\(^3\) Bee species can differ in preference to flower height, time of flower visitation and within-flower behavior, which has been related to body size.\(^4\) Bee size has also been linked as a predictor of foraging behavior. Based on homing research, feeder training and interpretation of bee dance, it has been reported that larger bees have disproportionately larger foraging distances than smaller bees.\(^5\)

However, foraging behavior is also influenced by non-size-related variables such as plant distribution and density,\(^6\) nectar preferences\(^7\) and plant attributes.\(^8\) A. mellifera will abandon or avoid cucurbit resources for other floral sources (perhaps because pollen on some cucurbits is very sticky, which may make energy expenditure too expensive for the nutritional reward), and bumblebees are known to avoid visiting strawberry flowers.\(^9\)

### 2.4 Nectar rewards

Plants use floral and extrafloral nectaries to attract pollinators.\(^24\)

The differences between floral and extrafloral nectaries may include location of the nectary on the plant (floral nectaries are in the flower, extrafloral nectaries are usually on the leaf or stems), strategic use by the plant of the nectary (pollinator attraction versus defense mechanism) and compounds excreted through the nectary other than the three main sugars: sucrose, glucose and fructose.\(^10\) In some cases, extrafloral nectaries are preferred over floral nectaries (e.g. cotton).

Honey bees, bumblebees and stingless bees (Melipona species) seem to prefer nectar from nectaries with sucrose concentrations in the 50–65% range.\(^25\)–\(^27\) This ‘preference’ appears to be based on the licking behavior of these bees, and this range provides the fastest energy intake compared with concentrations outside this range.\(^25\)–\(^28\) Recent research highlights the role of nectar temperature and feeding and suggests that warmer and less viscous nectar may be preferred by some bees to cooler higher-sugar nectar.\(^29\)

Orchid bees, however, unlike most other bees, suck nectar (like Lepidoptera) and can obtain the fastest energy intake by feeding on nectar with lower sugar concentrations (30–40%).\(^25\)–\(^30\) These preferences for sugar concentration were obtained from a variety of testing methods, including field observation.\(^26\)–\(^29\)\(^30\)

#### Table 1. Qualitative attractiveness ranking of ten US crops to bees and published sugar content in nectar

| Crop        | Attractiveness of crop pollen to honey bees | Attractiveness of crop nectar to honey bees | Attractiveness of crop to bumblebees | Attractiveness of crop to solitary bees | Sugar content of nectar, % |
|-------------|---------------------------------------------|--------------------------------------------|-------------------------------------|----------------------------------------|--------------------------|
| Canola      | ++                                          | ++                                        | +                                   | +                                     | 29–84\(^{39,40}\)         |
| Citrus      | ++                                          | ++                                        | +                                   | +                                     | 23–37\(^{41}\)           |
| Almond      | ++                                          | +                                         | +                                   | +                                     | 16–32\(^{42}\)           |
| Soybean     | +                                            | +                                         | +                                   | +                                     | 23–60\(^{43}\)           |
| Cucurbit    | +                                            | +                                         | +                                   | +                                     | 20–50\(^{43–45}\)       |
| Strawberry  | +                                            | +                                         | +                                   | +                                     | 26–36\(^{46}\)           |
| Cotton      | –                                            | ++                                        | +                                   | +                                     | 18–34\(^{46,47}\)       |
| Corn        | +                                            | –                                         | –                                   | +                                     | None                     |
| Potato      | –                                            | –                                         | +                                   | +                                     | None                     |
| Wheat       | –                                            | –                                         | –                                   | +                                     | None                     |

\(^a\) Based on the USDA.\(^3\)
almond, soybean, cucurbits, strawberry, cotton, corn, potato and wheat. Data on sugar content in the nectar of these crops are shown in Table 1. While not a direct match to attractiveness ranking based on the USDA’s approach, percentage sugar content of nectar in those crops reveals a similar pattern (with the exception of soybean and cucurbits). In other words (and regardless of the variation in sugar concentration within a crop), canola and citrus have higher sugar content than the other crops and sit at the high end of the attractiveness scale; cucurbits, strawberry, almonds and cotton have middle-of-the-range sugar contents compared with the other crops and sit in the middle of the attractiveness scale; corn, potato and wheat are found at the bottom of both (Table 1). Soybean and cucurbits, based on sugar content, look ‘more attractive’ than is apparent when using the USDA ranking scheme. There is evidence in the literature to supportApis preferences for soybean: although soybean is self-pollinating, its flowers can produce nectar that is attractive to A. mellifera50 and of a high quality compared with other crops.37 There seems to be a geographic component to this preference. Unlike the warmer southern US states where soybean produces nectar, soybean flowers may not open or produce nectar in the cooler US states.7 While nectar sugar content may make crops attractive to bees, other plant-specific factors may make plants unattractive, regardless of sugar content (refer to above sections). Based on a number of lines of evidence (e.g. honey bees, bumblebees and solitary bees prefer nectar with sugar concentrations in the narrow range 50–65%; bees are hardwired to communicate sugar concentration in nectar to hive members through dance and auditory cues; the diet of bees is dominated by nectar; sugar concentration in nectar trends with qualitative rankings of attractiveness based on observations on bees on crops), while not perfect, sugar content in nectar could be a useful metric by which to refine pollinator risk assessments.

| EEC (µg AI bee⁻¹) | TRV (µg AI bee⁻¹) | CAF^a | RQ^b | RQ calculation | Crop |
|------------------|------------------|------|-----|---------------|-----|
| 0.12             | 0.25             | None (consistent with current EPA approach) | 0.48 | 12/25 | All crops regardless of sugar nectar concentration |
| 0.024            | 0.25             | 0.2  | 0.096 | (2.4*0.2)/25 | Those with 10% sugar in nectar |
| 0.048            | 0.25             | 0.4  | 0.192 | (4.8*0.4)/25 | Those with 20% sugar in nectar |
| 0.072            | 0.25             | 0.6  | 0.288 | (7.2*0.6)/25 | Those with 30% sugar in nectar |
| 0.096            | 0.25             | 0.8  | 0.384 | (9.6*0.8)/25 | Those with 40% sugar in nectar |
| 0.12             | 0.25             | 1    | 0.48  | (12*1)/25  | Those with >50% sugar in nectar |

^a The crop attractiveness factor was calculated by dividing the optimum sugar concentration for bees (50%) by the sugar concentration in nectar of a crop (%). For example, a CAF of 0.2 is 10%/50%.

^b Bold indicates RQ > LOC.

4 SUGGESTED USE INTO THE RISK ASSESSMENT PARADIGM

4.1 Crop attractiveness factor

An assumption in the USEPA guidance for calculating tier I risk to pollinators from exposure to pesticides is that daily consumption rates are based on a sugar content in nectar of 30% (the EFSA approach1 is based on even less sugar in nectar, with 15% assumed for honey bees and bumblebees and 10% for solitary bees). This means that the risk quotient (RQ) for acute effects (i.e. the ratio of exposure (EEC) and the toxicity reference value (oral or contact LD₅₀)), which is subsequently compared to an LOC of 0.4, is based on sugar contents in plants that honey bees, bumblebees and stingless bees do not prefer. We suggest that the tier I process could be modified in a quantitative manner by adjusting the EEC in the calculation of an RQ (i.e. EEC/TRV) based on crop-specific sugar nectar concentration. By dividing the sugar nectar concentration in a specific crop by the preferred lower-end sugar nectar concentration of 50%,26–27 a crop attractiveness factor (CAF) can be calculated (Table 2). This preferred sugar nectar concentration applies to bees other than orchid bees, which as noted previously, prefer lower sugar nectar concentrations and are not expected in agricultural areas of the United States.38 This CAF can then be multiplied by the EEC to yield a ‘crop attractiveness corrected’ EEC, which in turn can be used in the calculation of an RQ. To illustrate this point, assume an EEC of 0.12 µg active ingredient (AI) bee⁻¹ and an oral TRV of 0.25 µg AI bee⁻¹. The resultant RQ is 0.48, which exceeds the EPA LOC of 0.4 (Table 2). Regardless of the ‘attractiveness’ of the hypothetical crop in this example, the conclusion from the calculation of the RQ is unacceptable risk to pollinators from exposure to this AI (i.e. RQ > LOC). However, if the sugar nectar concentration for this hypothetical crop is 30%, which is less than the preferred range, the EEC can be corrected with a CAF of 0.6 (i.e. 0.3/0.5). The resulting RQ is 0.288, which is less than the EPA LOC, meaning acceptable risk to bees from exposure to the AI (Table 2). This approach can be used for a range of sugar nectar concentrations up to the bee-preferred concentration of 50–65%, where CAF = 1 and the crop-specific RQ is equivalent to the RQ for all crops regardless of sugar nectar concentration (i.e. consistent with the current EPA approach) (Table 2). As these examples illustrate, an EEC adjusted with a CAF returns an RQ that better accounts for the fundamental principle upon which ecological risk assessments are based: the interaction among receptor (bee), toxicity and exposure (based on attractiveness).

4.2 Inclusion of crops in the tier I process

What is more, the USEPA states, ‘This LOC [0.4] is intended to be conservative and serve as a reasonable screen for determining whether higher-tier testing is needed’.2 While this may be true, the conservatism (i.e. overprediction) not only applies in the calculation of risk but also in the plants that are assessed in tier I (i.e. plants that are not attractive to bees are carried forward through the risk process and scored against the same LOC). Sugar nectar concentration could also be used as a way to triage the inclusion of crops in the tier I process. For example, if nectar is absent
from a crop (and there is evidence of crop unattractiveness), there is no need to complete a quantitative assessment as the exposure pathway between bee and pesticide is negligible. Rather, a qualitative discussion of crop–pollinator interaction should be provided in the risk assessment process to justify to regulators the inclusion of crops in this category. In this paper, potato and wheat are examples of such crops: both are unattractive to bees and provide no nectar, and neither honey bees nor other bees seek these crops or are observed to forage in the crop. Alternatively, in cases where nectar sugar concentration is >30% or there is evidence of attractiveness to some bees (e.g. corn, strawberry, cotton), or high attractiveness to most bees (e.g. canola, citrus), inclusion of these crops in the formal tier I assessment plan is warranted. However, in cases where receptor–toxicity–exposure interactions are possible but temporally and spatially limited (e.g. corn does not provide nectar but is slightly attractive to bees, especially during pollen shed when it is one of few plants that bloom), a qualitative discussion about pollinator–crop interaction could be provided in tandem with the quantitative risk assessment (i.e. RQ versus LOC of 0.4). We recognize that the LOC of 0.4 has not been linked to detrimental effects in intact colonies, and that this LOC is based on an effect level that is consistent with control mortality in laboratory-based studies (i.e. 10%). Exceedances of this LOC should not indicate, in isolation and without other lines of evidence, unacceptable risk. If in these cases the RQ exceeds the LOC, the crop and pesticide should be assessed further against tier II and III guidance.

5 PROPOSED METHOD AND DISCUSSION

The interaction among receptor, toxicity and exposure is fundamental to the assessment of pollinator risk from exposure to pesticides. Conservatism in any of these variables results in risk characterizations that can be overly protective, which in turn can be used in regulatory decision. Use of a quantitative metric like nectar sugar concentration can be applied to both US EPA and EFSA pollinator risk assessment schemes and can provide a more realistic and biologically/agronomically defensible risk assessment. What is more, sugar contents in nectar for numerous crops are easily obtained from the published scientific literature. However, an uncertainty with this proposed approach is known variability in sugar concentration within crops. For example, sugar concentrations from 29 to 84% have been reported for canola (Table 1), meaning CAF of 0.6–1 could be applied in the risk assessment of this crop. If novel data are required to refine a sugar concentration for a given season or time period, they can be generated easily and cost effectively on a case-by-case basis using a refractometer (generally less than a few hundred dollars) and repeatable standard operating procedure. Registrants, extension universities and other researchers are often conducting field research on crops, and during these times nectar could be collected and assessed for sugar concentration to provide data for reducing uncertainty.

The method proposed here is one way of modifying the exposure component of the risk assessment with a quantitative metric of attractiveness (sugar nectar concentration). This paper is meant to invite discussion on incorporating such changes in the risk assessment process.

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