Science of the Total Environment 956 (2024) 177208

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

An investigation of spray drift deposition of glyphosate from an herbicide spraying train and its potential impact on non-target vegetation and railway ditches

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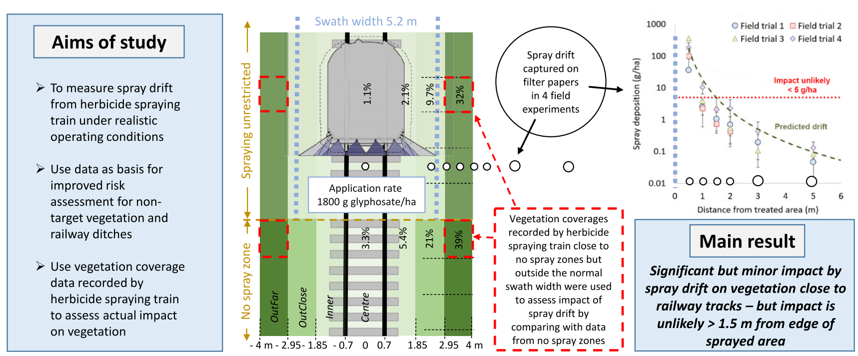
HIGHLIGHTS

- Spray drift from herbicide spraying train was measured in four field experiments.
- Average spray deposition declined from 1800 g a.e./ha to around 5 g/ha within 1 m.
- Impact on vegetation deemed likely <1 m but unlikely >1.5 m from sprayed area.
- Vegetation coverages recorded by herbicide spraying train were used to assess impact.
- Vegetation in a zone 0.35 to 1.4 m from the sprayed area was impacted by drift.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jay Gan

Keywords:
Railways
Glyphosate
Spray-drift
Vegetation
Ditches

ABSTRACT

Spray drift of glyphosate has the potential to affect non-target vegetation and surface waters close to the application area. To assess the likelihood of such impact along Swedish railways, four field experiments were conducted at three railway sites during 2019 and 2020. An herbicide spraying train applied herbicide *Roundup Ultra* (glyphosate) at speeds of 33 to 48 km/h. Quantitative filter papers were placed at 0.5, 1, 1.5, 2, 3 and 5 m distances to capture spray droplets. Wind speeds were low (0–2 m/s), but were found to be representative of normal operating conditions. Spray deposition decreased rapidly with distance, declining from 1800 g a.e./ha to an average of 5 g/ha within 1 m. Predicted 90th percentile drift rates suggested potential impact on vegetation within distances <1 m, where 90th percentile spray deposition would range from full dose to 18 g/ha. Beyond 1.5 m from the sprayed area, impact on vegetation was deemed unlikely. The potential concentrations in ditches near railways did not exceed the 100 μg glyphosate/L environmental quality standard even for ditches situated only 0.5 m from the sprayed area, indicating low risk to ditches or final recipients. Actual impact on vegetation was assessed using weed coverage data recorded by the herbicide spraying train itself. We extracted average weed coverages for 10 m sections around the edges of no spray zones and focused on the outermost sections surveyed, 0.35 to 1.4 m outside the application area. Predicted 90th percentile glyphosate deposition ranged

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https://doi.org/10.1016/j.scitotenv.2024.177208
Received 4 July 2024; Received in revised form 23 October 2024; Accepted 23 October 2024
Available online 6 November 2024

from 565 to 6 g/ha, averaging 80 g/ha in this zone. By comparing no spray zones to adjacent track sections, and tracks treated with glyphosate in 2019 to those that were not, we demonstrate that there is a statistically significant but relatively minor effect of spray drift on non-target vegetation close to the track.

1. Introduction

The literature on the environmental fate of herbicides on railways has primarily focused on assessing the microbial degradation or leaching potential of the substances in question (Börjesson et al., 2004; Buerge et al., 2024, 2020; Cederlund, 2022; Cederlund et al., 2012, 2007; Jarvis et al., 2006; Ramwell et al., 2004). However, despite the fact that there is a growing literature that evaluates the effects of spray drift in the agricultural setting on non-target plants (e.g. Moore et al., 2022; Perkins et al., 2022; Strandberg et al., 2021), comparably little attention has been paid to investigating spray drift and its potential impact on areas immediately surrounding railway tracks. Only one peer-reviewed paper describing results of spray drift measurements from an herbicide spraying train has been published previously (Wygoda et al., 2006). Some additional studies have been performed, including some measurements reported from Hungary (László, 2014; report not publicly available) and a recent study from France (Douzals et al., 2023) that was presented at a conference in 2023. Notably, most studies have focused measurements primarily on distances further out from the sprayed area, where the potential consequences of spray drift might be larger, but have neglected measurements closer to the track, where there is an increased likelihood of impact.

Spray drift patterns from railway applications may differ in several respects compared to spray drift from agricultural sprayers. Herbicide spraying trains often operate at relatively high speeds, typically 40–50 km/h, considerably faster than most field sprayers, which could be a risk factor. However, because of the high speeds, herbicide-spraying trains normally employ nozzles of types that produce a relatively coarse droplet distribution, limiting the overall drift potential. Most modern trains also employ some type of weed detection and spot application systems that can reduce the amounts of product being used significantly (Antuniassi et al., 2004). Another difference is that the lateral propagation of the sprayed area is naturally limited on railways, where usually only one track is sprayed at the same time, or at most two parallel tracks, whereas on an agricultural field, spray drift may be accumulated from many parallel swaths with the sprayer. An exemption to this rule would be marshalling yards where there are many parallel tracks. However, these are rarely treated with herbicide spraying trains, but more often with backpack sprayers or sprayers mounted on all-terrain vehicles, and are less often situated next to sensitive areas.

For several years, the herbicide of choice for European railway operators has been glyphosate. However, recently several countries have started moving away from glyphosate towards alternatives such as pelargonic acid, usually, but not always, applied in a combination with a sulfonylurea such as flazasulfuron for synergistic effect (Kilian and Marienhagen, 2017; Poiger et al., 2024) or flumioxazine (Zingelmann et al., 2022). Still, even though public pressure has been mounting to replace glyphosate, evidence suggests that at least from a groundwater protection point of view glyphosate is one of the better options for railways due to its relatively low mobility (Buerge et al., 2024; Cederlund, 2022). However, one aspect that has not been considered much is the potential impact of spray drift of glyphosate on non-target species and surface waters close to the area of application. Because glyphosate is an herbicide, plants are likely the organisms that would be most at risk from such spray deposition. Cederlund (2017) reviewed the effects of glyphosate spray drift on non-target terrestrial plants and found that restricting spray drift deposition rates to below 5 g/ha would protect 95 % of vascular plants against minor effects of spray drift. This gives us a reasonably conservative value against which to evaluate the damage potential of any measured or modelled drift data towards vegetation. Another concern may be railway ditches, which are often part of the railway drainage infrastructure. Such ditches can be situated close to the track and can sometimes be water-filled, especially after heavy rains or if the drainage system is poorly maintained. Ditches may potentially harbour sensitive aquatic species or perhaps direct water into recipients that need to be protected. Recently, during the re-registration process of glyphosate in the EU, a railway scenario (application of 1800 g glyphosate/ha; twice/year), was included under the representative uses that were evaluated, and the impact of spray drift on organisms and railway ditches was assessed based on results from the HardSPEC model (EFSA et al., 2023). This model was developed for estimating exposures from herbicide applications on hard surfaces and contains both a railway groundwater and a railway ditch scenario (Hollis et al., 2017). The risk assessment did identify risks towards non-target vegetation and recommended 90 % drift-reducing nozzles as a risk mitigation measure. However, the risk to railway ditches was found to be acceptable. It is noteworthy that the model was parameterized for UK conditions and that the data set on spray drift that was used for developing the model was obtained from a confidential report on spray drift from a UK train using Radiarc nozzles (Parkin and Miller, 2004). This nozzle type is not used on most herbicide spraying trains operating on European railways and thus it is uncertain how representative the modelled results are for typical railway applications (and assessing this is made more difficult by the fact that the report is not publically available). More field data on spray drift from herbicide spraying trains would thus be useful for reducing the uncertainty and improving the risk assessment.

However, even though wind drift can be measured, and be determined to be at levels that are likely to have an impact on vegetation close to the sprayed area, such effects may be difficult to demonstrate in practice, especially if the drift rates are low and effects subtle. One possibility, that we explore in this paper, could be to utilize the weed detection system of herbicide spraying trains, which can provide high-resolution datasets of vegetation coverages along the track, even in areas where they are not spraying, to assess such effects. By a lucky coincidence, during 2019–2020, the herbicide spraying train in use in Sweden (operated by *Weedfree on Track*) was configured to measure vegetation coverages not only in the central areas of the track, but also just outside the area being sprayed, in the zone that would potentially be most affected by spray drift. In the present study, we took advantage of this fact and utilized the multitude of no spray zones that are dispersed along the Swedish railway network for protection of surface waters and other sensitive areas, as impromptu untreated control surfaces.

Thus, the overall aim of this study was to assess the likelihood of environmental impact from spray drift deposition of glyphosate when applied to railways. This was pursued in three ways:

Firstly, by characterizing spray drift deposition from an herbicide spraying train operated under realistic conditions. Secondly, by using this deposition data for an improved risk characterization of glyphosate use along Swedish railways, with a particular focus on the potential for impact on nearby vegetation and railway ditches. Thirdly, by assessing the actual impact of spray drift of glyphosate on vegetation along Swedish railways by utilizing weed coverage data recorded by the herbicide spraying train during its normal spraying operations, and thus, if possible, corroborating the risk characterization.

2. Methods

2.1. Spray drift field trials

Four spray drift trials were conducted, two in 2019 and two in 2020, at three field sites (Fig. S1). At the Bruzaholm site, which was used for trials 1 and 3, the track ran through a recent clear-cutting. At the Grycksbo site, which was used for trial 2, the track ran close to a lake, but with a few trees partially shielding the railway, and with an open paddock on the other side. At the Arboga site, which was used for trial 4, the track ran through an open field next to a road, with an even uncultivated area between the road and railway where measurement could take place. An extended description of the field sites is provided in the supplementary materials.

Wind speed and direction were recorded using a Kestrel 5500 anemometer mounted with a vane on a tripod at a height of about 1,8 m above ground and placed at the centre of the track, just prior to the passage of the train. In addition, average wind speeds are routinely recorded by an Airmar 200WX weather station on the herbicide spraying train itself, and these figures were reported by *Weedfree on Track*. Spray deposition was captured on ashless quantitative filter papers (grade 00H, Munktell) with a diameter of 110 mm that were attached using paper clips directly to special metal mounts roughly 10–15 cm above the ground. For distances exceeding 3 m from the edge of the sprayed area, larger filter papers with a diameter of 150 mm were used to increase the sensitivity of the assay. These larger papers were held in place inside plastic petri dishes, with an interior diameter of 140 mm, which were placed on top of the mounts. The mounts were placed at the centre of the track at 0 m, and at 2.5, 3.1, 3.6, 4.1, 4.6, 5.6 and 7.7 m from the centre, corresponding to −2.6, −0.1, 0.5, 1, 1.5, 2, 3 and 5 m distance from the nearest edge of the sprayed area. The placement was adjusted depending on the prevailing wind direction, either selectively towards one side (5 transects) or both sides (3 transects) of the track, resulting in 4 to 6 replications of each sampling distance at each site. Transects were placed >5 to 10 m apart. For details concerning the placement at the individual sites, see Fig. S2. Any plants that were deemed tall enough to obstruct the airflow around the filter papers were manually removed before the application. Paper-based samplers, such as the filter papers used in this study, are among the most commonly used and more suitable sampling methods for measuring off target deposition of pesticides (Munjanja et al., 2020). Filter papers readily adsorb spray droplets, thus potentially protecting them from UV-degradation and volatilization, yet are easy to extract for analysis. Many spray drift studies utilize a fluorescent dye that is quantified by spectroscopy or image analysis, which is added to or used instead of the actual pesticide formulation in order to reduce costs and/or facilitate analysis. It has been shown that using trace dyes can give comparable results, to analysing the active ingredient, if recovery differences are accounted for (Szarka et al., 2021). However, by applying the formulation as is and analysing glyphosate directly, we can disregard any potential doubts about the dye having a different viscosity, surface tension or droplet size distribution compared to the commercial formulations, factors well known to influence the risk of drift (Hilz and Vermeer, 2013).

All trials were carried out within the regular schedule of operation of the spraying train, from the contractor *Weedfree on Track*, so the sites were treated during the late evening/early morning. The herbicide spraying train did not stop at the experimental sites, but the operators were pre-instructed to activate all nozzle sections of the train (excluding the outermost set that are never used in Sweden; see description below) when passing over the field sites in order to simulate a worst-case scenario. The application rate was 5 L Roundup Bio/ha (equivalent to 1800 g glyphosate/ha) and the swath width used was 5.2 m.

The train is equipped with an optical sensor mounted at the front of the engine, that continuously records weed coverages (in %) at a longitudinal resolution of about 1 m. During 2019–2020, the sensor output (image) was divided laterally into 9 zones Table 1, and weed coverages recorded in these zones controlled a combination of 56 spray nozzles (VeeJet Flat Spray nozzles of sizes 10 to 50) arranged in 10 sections, each section comprising four or eight nozzles. Which nozzles of each section that are activated is automatically controlled in order to maintain a constant application rate at variable speeds of operation. The recommended average spraying volume was 250 L/ha and the spraying pressure was 2 bar. The measured height of the nozzle sections from the rail crown were as follows: 46 cm for the two sections corresponding to zone 5, 47 cm for zones 4 and 6, 64 cm for zones 3 and 7, and 81.5 (slope) to 86.5 cm (plane) for zones 1, 2, 8 and 9. Because the swath width in Sweden was narrower (5.2 m) than in other countries where the train was operating (8 m), the nozzle configuration was altered, and the outermost nozzles sections were not in use. However, the vegetation zone division was kept, so that vegetation coverages were still being recorded outside the sprayed area (Fig. 1). In addition to weed coverages the system also records spraying state, i.e., whether a nozzle is active (spraying state = 1) in a particular nozzle section or not (spraying state = 0).

Table 1
Overview of vegetation zones.

Zone no	Distance from centre of track (m)	Spraying status	Our designation
1	−4. to −2.95	Not sprayed	OutFar
2	−2.95 to −1.85	Partially sprayed (68 %)	OutClose
3	−1.85 to −1.55	Sprayed	Inner
4	−1.55 to −0.7	Sprayed	Inner
5	−0.7 to 0.7	Sprayed	Centre
6	0.7 to 1.55	Sprayed	Inner
7	1.55 to 1.85	Sprayed	Inner
8	1.85 to 2.95	Partially sprayed (68 %)	OutClose
9	2.95 to 4	Not sprayed	OutFar

2.2. Analysis of glyphosate

Glyphosate concentrations on the filter papers were analysed by *Eurofins Food & Feed Testing*, Lidköping, Sweden. The whole filter papers were extracted in Milli-Q water together with an internal specific standard. The average recovery was 104 %. Aliquots of the extract were derivatized with 9-fluorenylmethyl chloroformate (FMOC) followed by purification using solid phase extraction on a Strata-X Reverse Phase Solid Phase Extraction column and concentration by evaporation. Samples were diluted in ammonium acetate buffert/methanol and analysed on an Agilent HPLC 1100 coupled with a Sciex API 4000LC-MS/MS.

2.3. Treatment of spray deposition data from the field trials

All deposition data were recalculated as g/ha based on the surface area of the filter papers. Because the applied amounts varied a bit between the different trials (Table 2), for purposes of modelling the drift, all values were further normalized by expressing them as a percentage of the applied amounts measured at −0.1 m (i.e., just within the directly sprayed area) in the respective trial. The normalized 90th percentile drift values were fitted using a simple power-function:

$$y = k \times x^{m}, \tag{1}$$

where x is the distance from the sprayed area in meters and k and m are fitting parameters.

The average spray deposition ($f_{average}$) over a zone or ditch stretching from point a to point b outside the sprayed area is given by:

$$f_{average} = \frac{1}{b-a}\int_a^b f(x)dx \tag{2}$$

and was calculated here as:

$$f_{average} = \frac{1}{b-a} \times \frac{k\left(b^{m+1} - a^{m+1}\right)}{m+1}, \tag{3}$$

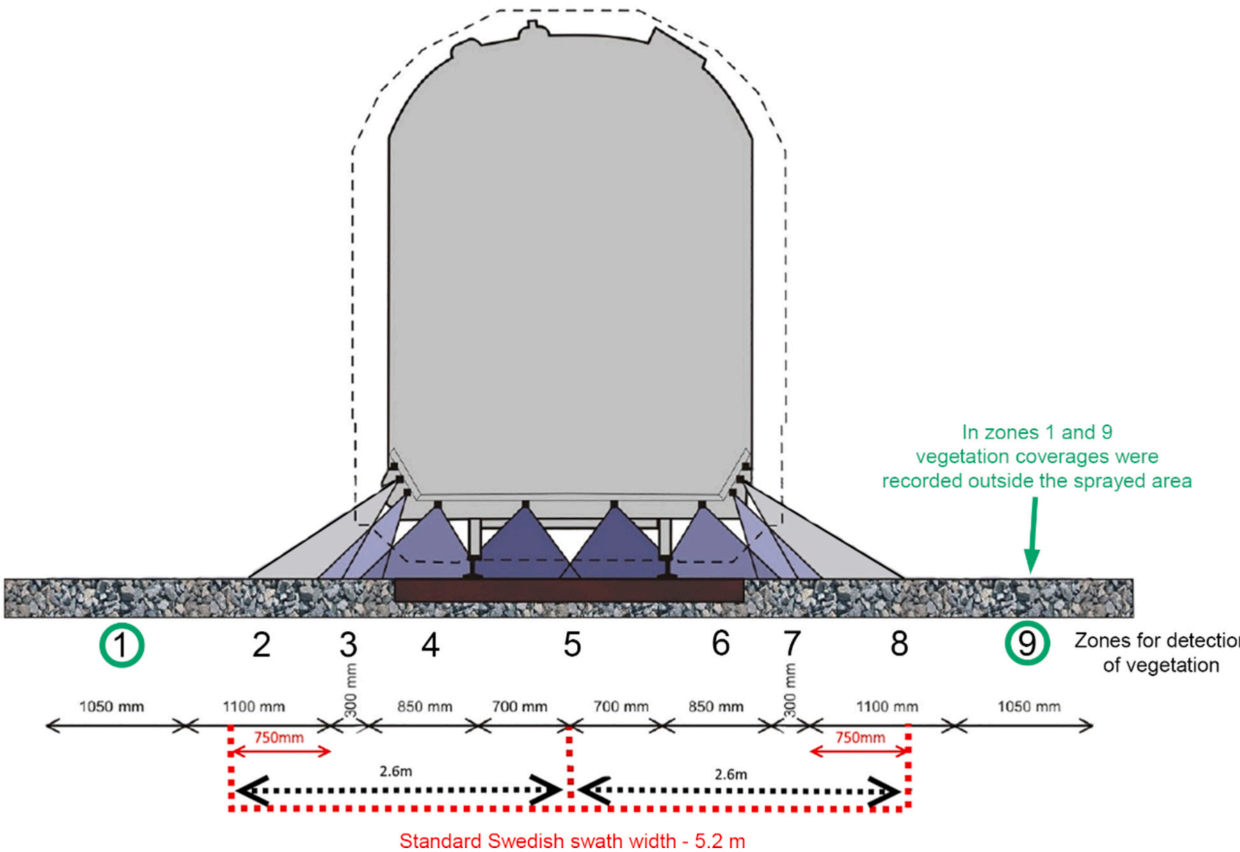

Fig. 1. Configuration of the spraying train in Sweden during summer 2020. Due to the narrower swath width of only 5.2 m, the outermost nozzle sections were not in use. Vegetation was detected in nine zones (see Table 1 for a comparison and for our designations), where the outermost zones (one and nine) recorded vegetation coverages outside the directly sprayed area.

Table 2
Overview of experimental conditions during field trials.

	Time of day	Wind speed – anemometer (m/s)	Wind speed – spraying train (m/s)	Travel speed (km/h)	Temperature (°C)	Relative humidity (%)	Estimated application rate[a] (g/ha)
Trial 1	20:56	0.0	0.9	48	11[b]	65[b]	1756
Trial 2	04:34	0.5	1.3	46	18[b]	79[b]	1977
Trial 3	20:47	1.0	2.0	41	14	50	1573
Trial 4	22:17	0.0	1.8	33	16[b]	46[b]	1795

[a] As determined by filter papers placed within the sprayed area – target application rate was 1800 g/ha.
[b] As determined by nearby climate station.

where k and m are the variables from the regression equation of the 90th percentile spray deposition, and where a and b denote the distance in meter from the edge of the sprayed area, i.e. assuming that spray deposition declines with distance as modelled in Fig. 2.

Potential concentrations in ditches were calculated making the following assumptions: a distance to the ditch of 0.5 to 1 m from the sprayed area to its closest edge, a width of between 0.5 and 1 m, a triangular cross section, a depth of 0.2 m, and no interception by vegetation, adsorption to sediments in the ditch or degradation of the herbicide.

2.4. *Import of data on vegetation coverages and no spray zone positions into Optram*

In order to assess the potential impact of spray deposition from normal applications to the railway network we used data on vegetation coverages recorded by the herbicide spraying train itself. Data on weed coverages from 2020 was originally given coordinates based on the GPS equipment of the spraying train, with an estimated positioning error of a few meters, and was delivered to the Swedish Transport Administration (*Trafikverket*) from *Weedfree on Track* in GIS-format (geopackage). At *Trafikverket*, the dataset was processed in several ways in order to enable analysis and import into *Optram* (Optram Enterprise, version 6.2.27.19, Bentley Systems Incorporated), a railway corridor infrastructure management software in use with *Trafikverket* for monitoring among other things track quality parameters. Each data point was moved laterally to correspond to the nearest railway track using an edge snap function. Data points were then given attributes from the track such as, track number, track section etc. using a spatial join function. Data was then imported into *Optram* using a data import script and stored as measured

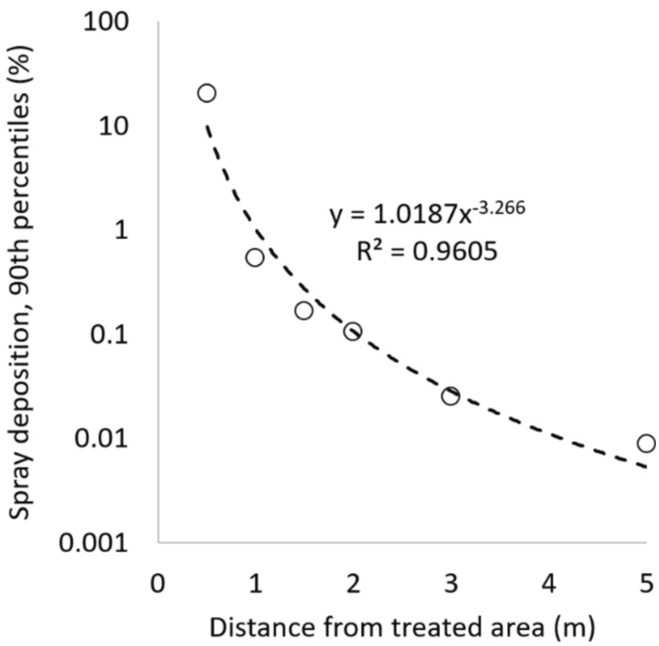

Fig. 2. Ninetieth percentiles spray deposition values expressed as percent of the application rate measured within the sprayed area fitted with a power function.

data/"survey" (one data point per meter and occasion). Some sections were not completely imported e.g., due to a lack of track designations in *Optram* (some side tracks lack designation) or due to errors in the positioning. However, it is estimated that only <1 % of the total data points could not be imported.

An independent dataset on the positioning of no spray zones (NSZs) was also imported into *Optram* (for several years). This dataset was also slightly processed by adjusting data type formats, adding Optram track sections and by adjusting erroneous track designations. Import into *Optram* was manual (DLD-file) and data was stored as an event set in the database. An estimated 1–2 % of the total length of NSZs could not be imported.

2.5. Data treatment within Optram/extraction of data

Weed coverages were originally measured in 9 different zones (as described above). However, in order to facilitate the data analysis, vegetation zones were combined in *Optram* into only four zones prior to our analysis. These zones were designated *OutFar* (zone 1 + 9; not sprayed; 1.05 m wide x 2), *OutClose* (zones 2 + 8; partially sprayed; 1.1 m wide x 2), *Inner* (zones 3 and 4 + 6 and 7; sprayed; 1.15 m wide x 2) and *Centre* (zone 5; centre of track between the rails; 1.4 m). An overview is given in Fig. 1 and Table 1.

A script that accomplished several things was run in *Optram* in order to analyse sections of track close to the edges of NSZs. First, NSZs from 2019 were loaded. Different types of NSZs were combined, to create a non-overlapping layer. NSZs shorter than 2 m and NSZ closer than 30 m from ballast free tracks (mainly steel bridges) were removed. Average weed coverages for eight 10 m sections surrounding the edges of NSZs (i.e., 30 to 40, 20 to 30, 10 to 20 and 0 to 10 m outside the NSZ edge and the same sections within the NSZ) were calculated for each of the four vegetation zones. The resulting dataset, comprising vegetation coverages from around 13,493 NSZ edges, was exported to Excel for further processing.

Several parts of the exported dataset were then manually excluded to avoid incorporating faulty or misleading information into the final analysis. Short (< 20 m; N = 3432) NSZ were completely excluded. Similarly, when collating vegetation coverages for 10 to 20, 20 to 30 or 30 to 40 m sections within NSZ, NSZs shorter than 40 m (N = 4216), 60 m (N = 899) and 80 m (N = 545), were selectively excluded. In cases where several measurements were available for the same NSZ edge, as could be the case if the herbicide spraying train passed multiple times over the same section of track, the weed coverages recorded during the spraying operation (usually the first measurements in the season) were used and the other measurements excluded. A total of N = 3532 such double measurements were removed. Any NSZs situated on marshalling yards (N = 1093) or surrounding railway bridges (N = 864; some steel bridges removed already in previous step) were removed. Data from three track sections 376A, 376B and 376C was completely removed (N = 105) because these sections had an ERTMS signalling system installed, which required a change of the locomotive and a recalibration of the measuring equipment, resulting in faulty vegetation coverage data being collected. A total of 4747 NSZ edges remained at this stage. This dataset was further split up depending on ballast type; "stone ballast" (Swedish "makadam"; N = 3923)), consisting of crushed rock/coarse gravel with a specified grain size distribution primarily between 31.5 and 63 mm (makadam class I) or between 11.2 and 31.5 mm (makadam class II), or "gravel ballast", consisting mainly of fine gravel or coarse sand (N = 863). Furthermore, it was split depending on whether the tracks were sprayed with a glyphosate-herbicide in 2019 (N = 1660 for stone ballast and N = 620 for gravel ballast) or not (N = 2255 for stone ballast and N = 124 for gravel ballast). NSZs for which a ballast classification was missing or where it was unclear if they were sprayed or not during 2019 were excluded (Fig. S3).

2.6. Statistical analysis

The differences between the average weed coverages were analysed using a non-parametric Steel-Dwass test ($\alpha = 0.05$). It was initially found that weed coverages in 10 m sections within the NSZ were not different from each other but that the influence of the NSZs extended outside their borders so that weed coverages at least in the 0 to 10 m and 10 to 20 m sections outside the NSZs were significantly elevated. In order to facilitate data treatment and interpretation while avoiding such edge effects and simultaneously maintaining the maximum number of comparisons possible, it was decided to focus on comparing the section 0 to 10 m within the NSZs (fewest data points discarded) with the section 30 to 40 m outside it (least affected by proximity to NSZs) for the analysis. For the analysis of potential effects of spray deposition on non-target plants we focused on comparing the coverages recorded in the OutFar zone (i.e. zone 1 + 9 in Fig. 1).

3. Results and discussion

3.1. Pattern and level of spray deposition

The average application rate in the four field experiments, as estimated by the filter papers placed on the track, within the swath, was 1775 g/ha, which was close to the target application rate of 1800 g/ha, indicating that overall the filter paper method is fairly reliable. However, the applied amounts varied between the field experiments (Table 2) and in some cases also systematically between the left and right side of the track. Because of this, spray drift values were normalized by expressing them as a percentage of the application rate as measured on the filter papers placed just within the sprayed area on the side closest to the side where spray drift was being monitored.

The measured spray deposition declined rapidly with distance down to a 90th percentile of only 0.53 % of the applied dose at 1 m distance, and then at a much slower rate further out, reaching 0.009 % at 5 m (Fig. 2). Notably, spray deposition in our experiment deviated significantly from basic drift values determined for field crops (Rautmann et al., 2001) with comparatively higher levels of drift seen close to the area of application but much lower levels of drift further out (Fig. 3). However, the level and pattern of deposition was similar to what has been seen in other spray drift trials with herbicide spraying trains

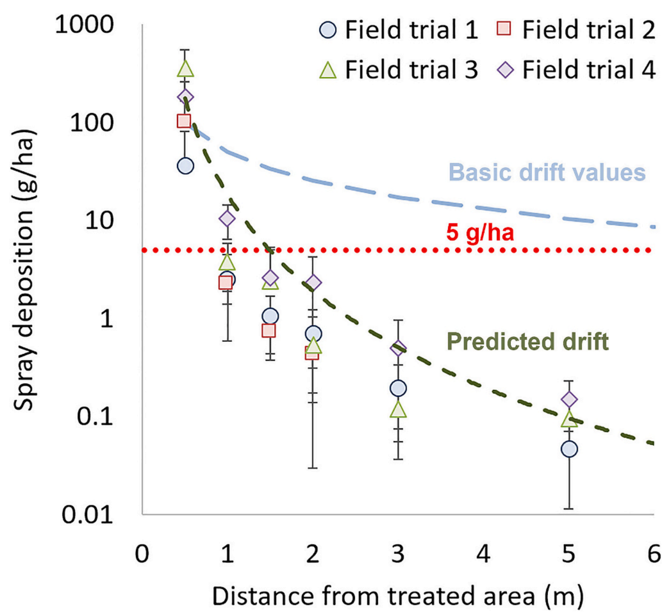

Fig. 3. Predicted 90th percentile drift values for an assumed application rate of 1800 g/ha (green dashed line) vs. measured spray deposition, average ± standard deviation, in the different field trials. Also shown (blue dashed line), are basic drift values for field crops assuming the same application rate (from Rautmann et al., 2001), and in the red dotted line, the level of 5 g/ha below which Cederlund, 2017 proposed that 95 % of vascular plants would be protected from minor effects of drift. Measurements at each sampling distance were replicated 4 (field trial 2), 5 (field trials 3 and 5) or 6 times (field trial 1).

(Douzals et al., 2023; László, 2014; Wygoda et al., 2006; Table S1). Both Wygoda et al. (2006) and Douzals et al. (2023) also noted that drift values were significantly lower than agricultural reference values. However, our study was the only one to measure drift at only 0.5 m from the sprayed area, and this close to the track, deposition was quite high, with a 90th percentile spray deposition of around 20 % of the overall application rate. This drift pattern is consistent with a relatively coarse droplet size distribution with only a minor proportion of smaller droplets that are more susceptible to drift (Arvidsson et al., 2011). Data provided by the nozzle manufacturer (*Spraying Systems Co.*) indicated that volume median diameter values (VMD) for all the nozzle types mounted on the train would exceed 500 μm at the spraying pressure used, and for many of the nozzles would exceed 800 or 1000 μm (Fig. S4).

One uncertainty about the obtained results is the effect that higher wind speeds could potentially have had on the results. Wind speeds during the four field trials were measured as only between 0 and 1 m/s by anemometer on site and as between 0.9 and 2 m/s by the herbicide spraying train (Table 2). It was hoped that at least one of the trials would be conducted at a wind speed at or close to 5 m/s, which is the maximum wind speed at which spraying is allowed on Swedish railways today, and with a wind direction directly perpendicular to the track, to represent a worst-case scenario. However, since the trials were all conducted during late evening/early morning wind speeds had always declined substantially before the trials were carried out. Wind speeds during Swedish summer nights, when spraying is normally conducted, are typically quite low, and this was confirmed when looking at wind-speeds recorded in the spray log of the herbicide train during four seasons of operation in Sweden (Fig. S5). Median wind speeds recorded in the spray logs were only 0.5, 0, 0, 0.4 during the 2019, 2020, 2021 and 2022 seasons, respectively, indicating that the prevailing wind conditions during the trials were typical of those encountered during normal operation of the train (Fig. S5). However, as indicated by the 90th percentile wind speeds, recorded as 2.9, 1.0, 0.90, 2.7 m/s for the different seasons, there were also a few occurrences of higher wind speeds, closer to the maximum limit; for the 2019 season, there were even a few cases where the wind speed was reported as exceeding the 5 m/s limit. Previous research from agriculture has shown that higher wind speeds increases drift at larger distances from the field, while it may even reduce drift close to the field edges (Wang and Rautmann, 2008). However, it is uncertain how increased wind speed would have affected the current results. Of note is that wind speeds were relatively low (0 to 1 m/s) in the study conducted by László (2014), but considerably higher (between 2.9 and 4 m/s) in the study by Wygoda et al. (2006). Douzals et al. (2023) conformed to ISO 22866 with 90 % of the wind speed data higher than 1 m/s and a maximum average wind speed below 5 m/s. Yet, these differences in wind speeds between the different studies were not obviously reflected in the results (Table S1), perhaps indicating that fluctuations in wind speeds below 5 m/s are not that crucial.

3.2. Likelihood of an impact on vegetation close to the track

For the risk assessment we fitted the 90th percentile spray deposition values with a simple power function, which provided an excellent fit ($R^2 = 0.96$) (Fig. 2). Such a function may not be suitable for extrapolation very far beyond the measured range but should be perfectly suitable for interpolation between the measured data points as attempted here. In addition, since the spray deposition further out from the track was so low, extrapolation beyond the measured range is likely irrelevant for the risk assessment anyway. Using the parameters of the model we calculated spray deposition in % at various distances from the track and then converted the values back to g a.e./ha assuming an application rate of 1800 g glyphosate/ha (and indirectly an application to the whole surface as was the case during the spray drift trials). At 1 m distance from the edge of the sprayed area the 90th percentile spray deposition was 1 % corresponding to 18 g/ha and this decreased down to 0.27 % or 4.9 g/ha at 1.5 m, and 0.051 % corresponding to 0.92 g/ha at 2.5 m (Fig. 2). These results can be compared to those of Cederlund (2017), who conducted a meta-analysis about impact of glyphosate spray drift on non-target terrestrial plants. He (I) concluded that a spray drift level below 5 g a.e./ha would protect approximately 95 % of higher plant species, while a spray drift level below 1 to 2 g a.e./ha would be almost completely protective. Thus, one could tentatively conclude that an impact on vegetation is likely at distances <1 m from the sprayed area, unlikely at distances >1.5 m and very unlikely at distances >2.5 m.

3.3. Weed coverages and spraying states around no spray zone edges

When studying the weed coverages for the 10 m track sections around the edges of NSZs it became clear that the influence of the NSZs extended beyond the protected area, with weed coverages gradually decreasing with distance to the NSZ. By contrast, weed coverages did not change significantly when moving further into the NSZ (Fig. S6). This pattern could be largely explained by studying the herbicide spraying state, where it became clear that the train tended stop spraying 10 to 20 m ahead of the NSZs (Fig. S7). Notably, in a few cases the data showed activation of the nozzles also within the NSZ, which we think can be largely attributed to a positioning error related to importing the datasets from the spraying train and on NSZ positions on the railway separately into *Optram,* rather than indicating actual spraying within NSZs in the field. In a few cases it was evident from visual inspection that while the train stopped spraying, the cessation of spraying and the NSZs did not line up well in *Optram* (Fig. S8). For the 0 to 10 m section within NSZs, nozzles were at least partially activated in around 10 to 12 % of cases for the OutClose zone. This declined to between 5 and 1.1 % of the cases for the 10 m sections further in, and activations were fewer towards the centre of the track (due to fewer weeds). However, the decline in spraying activity outside the NSZs appeared larger than the activation of nozzles within the NSZs, indicating that this decline was only partially due to the positioning uncertainty, but hinting towards a tendency of the train operator to shut down spraying prematurely when arriving at a

NSZ in order to “play it safe”. This latter tendency could also be observed in *Optram* (Fig. S9).

3.4. Impact of herbicide applications and spray drift on vegetation as measured by weed coverage data

Vegetation coverages were low, with an average coverage of at most a few % at the centre of the railway track, irrespective of ballast type, but increased further out from the track middle (Table 3; Figs. 4 and 5). Vegetation coverages were lower for railways with stone ballast than for those with gravel ballast, especially for the central parts of the track, with average vegetation coverages for the *Centre* and *Inner* zones recorded at between 0 and 1.3 % for stone ballast and 1.1 to 6.3 % for gravel ballast (Table 3). Vegetation coverages were significantly higher within NSZs as compared to just outside NSZs, demonstrating a persistent impact of the chemical weed control, even though differences were not very large in some instances. However, as glyphosate is not a pre-emergent herbicide it should perhaps not come as a surprise that the effect of a singular application is comparably small. Due to the lack of a long-lasting effect of glyphosate, *Trafikverket* have several times deemed it necessary to go for two applications per season in order to obtain sufficient levels of control, although this was not the case for 2019 or 2020. It should be noted, as the vegetation coverages were measured while herbicides were being applied during 2020, that what we are in fact seeing is mainly the effects of the weed control carried out during 2019. When studying tracks that were not treated in 2019 the differences between coverages within and outside NSZs declined but were still significant in most cases, indicating that there are probably also some accumulative effects from several successive years of herbicide treatments. It should be noted that apart from excluding certain types of NSZs we made no attempt to distinguish between certain types of NSZs, e.g., based on age (i.e. when they were created), and it is possible that this also confounded the results. Certain types of NSZ have been present for many years, whereas other types have been added more recently, and it is plausible that such “younger” NSZs would have lower vegetation coverages, thus contributing to smaller average differences. It was also noted that the positions of NSZs were not necessarily constant between years, but that they may shift position slightly, potentially leading to less distinct transitions between normal track and NSZs.

Notably, a small but significant difference was also seen between NSZs and treated track in the *OutFar* vegetation zone that lies just outside the area of application, at 2.95 to 4 m from the track middle, or 0.35 to 1.40 outside the edge of the sprayed area. On gravel ballast the vegetation coverage was 39 ± 24 % in the NSZs compared to 32 ± 22 % (Fig. 4), while on stone ballast the difference was only 40 ± 22 % vs 37 ± 22 % (Fig. 5), but still significant. Since this difference was seen just outside the area of application, it is most likely an indication of spray drift affecting the vegetation negatively. However, when studying vegetation coverages for tracks that were not treated with herbicides in 2019, the differences between NSZs and track sections close by declined and were not significant, indicating that such effects of spray drift may be transient. Calculating the anticipated spray deposition over this zone from Eq. (3) we arrive at 90th percentiles of 565 and 6 g/ha for the 0.35 and 1.4 m distances, with an average 90th percentile deposition of 80 g/ha for the OutFar zone. These levels of drift would clearly be enough to have a negative influence on vegetation, especially closer towards the track. Thus, this broadly confirms the risk assessment above where we concluded that an effect is likely at distances <1 m from the sprayed area. Unfortunately, we do not have any vegetation measurements in zones further out from the track to corroborate the tentative conclusion above of an effect on vegetation being unlikely >1.5 m from the sprayed area. However, the fact that the coverage differences were so small in the OutFar zone indicates that at least any persistent effects of spray drift would be minor further out from the track. Of course, the fact that vegetation coverages were measured one year after the last application means that any transient effects of low levels of drift, or qualitative effects, such as an effect on the number of flowers formed (e.g. Strandberg et al., 2021) or any effects on plant community composition would be difficult to spot in this dataset.

Spray drift is also known to be a potential driver for resistance development. Several, glyphosate resistant weeds have been identified along European railways and it is likely that this is only the top of the iceberg. Chodová et al. (2009) identified a horseweed (*Conyza canadensis*) with reduced susceptibility to glyphosate from the Prague-Bubny railway station in the Czech Republic and similarly Amaro-Blanco et al. (2019) identified both glyphosate resistant *C. canadensis* and *C. bonarensis* from railway margins in Andalusia, Spain. Also in Spain, Vazquez-Garcia et al. (2020) reported the first case of glyphosate resistant Johnsongrass (*Sorghum halepense*) in Europe, in plants collected from railways and freeways near Cordoba, where glyphosate was the main weed control tool. Finally, Bemowska-Kalabun et al. (2021) described the presence of glyphosate resistant *Geranium robertianum* collected from several railway stations in Poland, which potentially explains some of its “railway-wandering” ability (Wierzbicka et al., 2014). It is likely that the over-reliance on glyphosate as a weed control tool and a lack of properly implemented resistance management strategies by European railway operators is the ultimate cause of such resistance development. However, the proximate cause can potentially be found in the regular exposure of plants in the immediate vicinity of the treated track to sub-lethal glyphosate doses, allowing a gradual selection towards more resistant phenotypes. Low levels of glyphosate deposition around the edges of sprayed areas may lead to a situation where certain plant species in a community are favoured at the expense of more sensitive species, which could accelerate the selection for glyphosate resistance (Anunciato et al., 2022). Belz and Sinkkonen (2021) suggested that glyphosate doses around the ED_{10} response level would be of greatest practical importance for such selection processes to occur. Notably, from this perspective, the railway is essentially a continuous field edge, stretching through the landscape, perhaps making such considerations more relevant for railways than for agricultural fields. Of concern is also that railways, particularly the ones regularly applying glyphosate, may constitute an ideal means of transportation for glyphosate resistant plants across the landscape once they have evolved (Schoenenberger and D’Andrea, 2012) and may potentially contribute to the spread of glyphosate resistant weeds to or between agricultural fields.

Table 3
Average vegetation coverages measured close to (30 to 40 m) or within (0 to −10 m) no spray zones (NSZ) in 2020 ± standard deviations.

	Distance from track middle	Coverage (%)- gravel ballast treated 2019	Coverage (%)- gravel ballast untreated 2019	Coverage (%)- stone ballast treated 2019	Coverage (%)- stone ballast untreated 2019
Centre	0–0.7 m	1.1 ± 3.5	1.5 ± 3.6	0.0 ± 0.6	0.0 ± 0.3
	0–0.7 m NSZ	3.3 ± 6.3	2.0 ± 3.0	0.1 ± 1.2	0.1 ± 0.4
Inner	0.7–1.9 m	2.1 ± 5.6	4.0 ± 6.2	0.4 ± 1.9	1.0 ± 2.9
	0.7–1.9 m NSZ	5.4 ± 9.7	6.3 ± 7.4	1.3 ± 3.4	1.3 ± 3.5
OutClose	1.9–3 m	9.7 ± 14	22 ± 19	7.9 ± 11	12 ± 15
	1.9–3 m NSZ	21 ± 21	30 ± 20	16 ± 17	14 ± 17
OutFar	3–4.05 m	32 ± 22	53 ± 23	37 ± 22	28 ± 21
	3–4.05 m NSZ	39 ± 24	55 ± 24	40 ± 22	29 ± 22

3.5. Likelihood of an impact on railway ditches

The concentration of glyphosate in railway ditches did not exceed the environmental quality standard for surface water of 100 μg glyphosate/L in any of our scenarios (Fig. 6). Our calculations indicate that

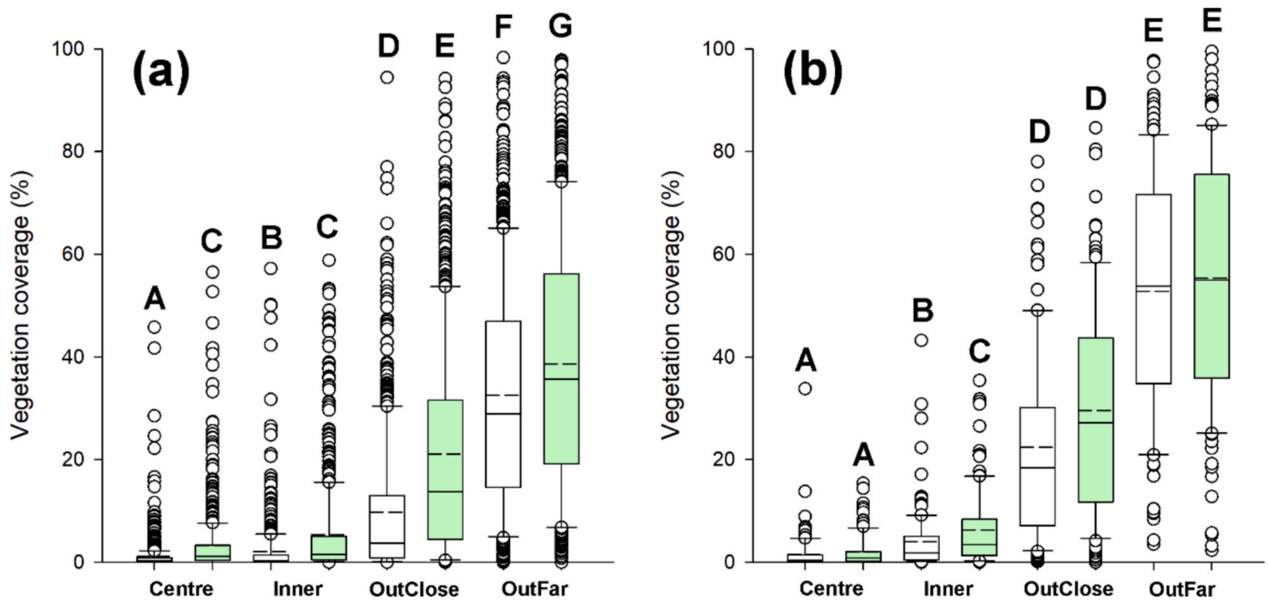

Fig. 4. Boxplots showing vegetation coverages measured in 2020, on railways with gravel ballast, for areas treated (a; $N = 620$) or not treated (b; $N = 124$) with herbicides in 2019, compared with vegetation coverages in corresponding no spray zones. White boxes show average vegetation coverages for sections 30 to 40 m outside no spray zones and green boxes show average vegetation coverages within no spray zones (0 to −10 m). Solid lines within boxes show medians and dashed lines show mean values. Boxes designated with the same capital letter were not statistically different in a Steel Dwass test (α = 0.05).

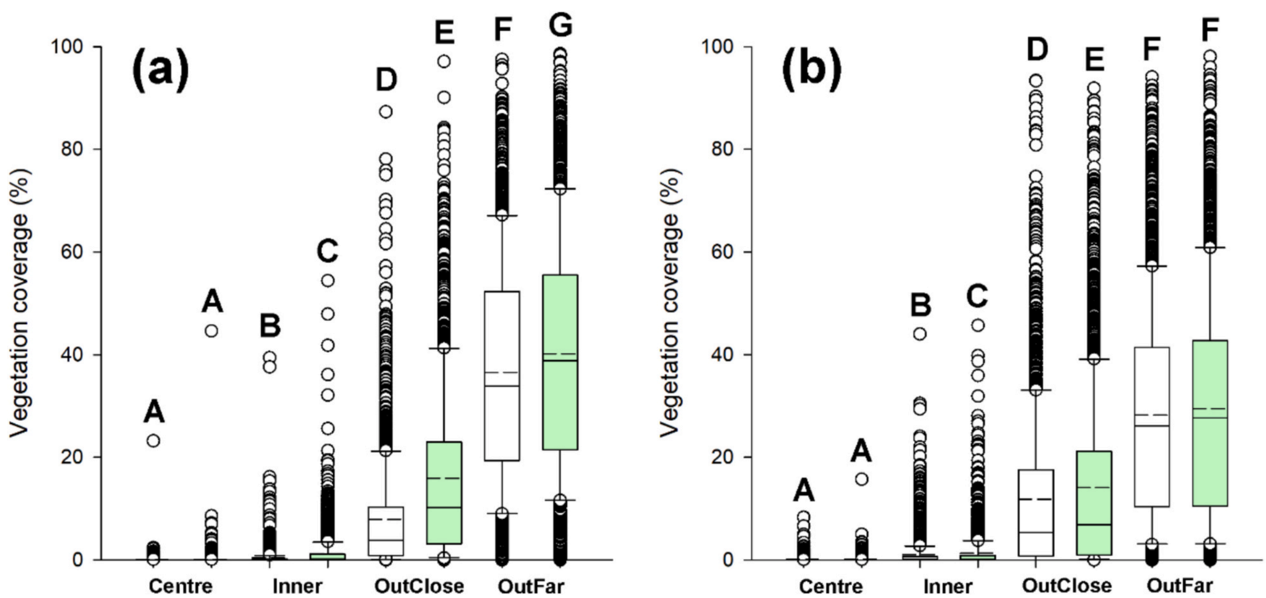

Fig. 5. Boxplots showing vegetation coverages measured in 2020, on railways with stone ballast, for areas treated (a; $N = 1660$) or not treated (b; $N = 2255$) with herbicides in 2019, compared with vegetation coverages in corresponding no spray zones. White boxes show average vegetation coverages for sections 30 to 40 m outside no spray zones and green boxes show average vegetation coverages within no spray zones (0 to −10 m). Solid lines within boxes show medians and dashed lines show mean values. Boxes designated with the same capital letter were not statistically different in a Steel Dwass test (α = 0.05).

this level could only conceivably be exceeded for very narrow or shallow ditches situated <0.5 m from the sprayed area. This suggests that the risk would also be low for surface water recipients since concentrations would be further diluted, as well as adsorbed and degraded before reaching any of these. Our findings broadly agrees with those of the recent renewal assessment of glyphosate in the EU, where the risk to railway ditches was found to be acceptable. In the EU assessment, a single application of 3600 g/ha was assessed using the railway ditch scenario of the HardSPEC model (Hollis et al., 2017). This scenario assumed a 1 m wide; 30 cm deep, trapezoid-shaped ditch situated 2.9 m from the sprayed area and accounted for interception by weeds, adsorption to sediments and degradation, yet suggested a ditch concentration of 9.458 μg glyphosate/L (Assessment Group on Glyphosate, 2021). By contrast, we assumed a shallower ditch with a triangular shape (both contributing to lower volume/less dilution), and no interception, adsorption or degradation at all. However, when we calculated ditch concentration from an assumed application rate of 3600 g/L and a for 1 m wide ditch situated at a distance of 2.9 m, based on our drift values and assumptions, we get a concentration of only 0.7 μg glyphosate/L. This suggests that the drift values used in the HardSPEC model, based on a confidential report from a spray drift trial in the UK with a train using Radiarc nozzles (Parkin and Miller, 2004), may be

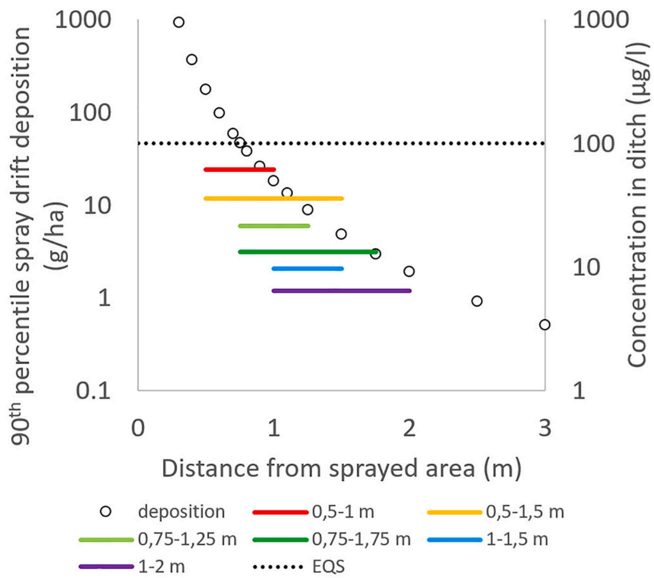

Fig. 6. Calculated concentrations in ditches at various distances from the sprayed area and with various widths assuming 90th percentile drift values. The environmental quality standard (EQS) for surface water of 100 µg glyphosate/l is shown as a dotted reference line.

significantly overestimating the drift potential of modern spray trains.

3.6. *Potential of vegetation data for railway managers*

One thing this study has demonstrated is the great potential for utilizing high-resolution datasets of vegetation measurements along railways. Delivery of such datasets from contractors conducting spraying operations is increasingly seen as a valuable product, which can provide additional value to railway managers. In our study, we focused only on the transition zones between no-spray zones and the rest of the track and were able to get a measure of how well the chemical weed control works long-term, as well as demonstrate an effect of spray-drift on vegetation close to the track. However, such data can be utilized for a variety of other purposes such as status description, for planning spraying operations and for the study of fundamental questions, such as what other factors influence the growth of plants on railways or the impacts that vegetation may have on the railway infrastructure itself. Further development of weed recognition systems are also likely to provide additional value to railway operators by helping them monitor the spread of invasive species. However, for such uses to become commonplace it is important that the data be delivered in a format that is easy for the end user to manage, while still enabling in-depth analysis.

4. Conclusions

Overall, our results imply that spray drift from herbicide spraying trains, such as the one in use in Sweden today, decreases rapidly with distance from the railway track and is below 1 % of the applied dose at distances exceeding 1 m from the sprayed area and below 0.1 % at distances exceeding 2.1 m. From the results, we believe that, with the current application rate of 1800 g glyphosate/ha, an effect on nearby vegetation is unlikely for distances exceeding 1.5 m and very unlikely for distances exceeding 2.5 m from the sprayed area. However, spray drift of glyphosate does reduce vegetation coverages in the immediate vicinity of the railway (< 1.5 m from the sprayed area), effects on community composition and resistance development are uncertain. The risk for surface waters including railway ditches is low, since our simulations show that the EQS for surface water of 100 µg glyphosate/L was not exceeded in any of our evaluated scenarios, despite making several worst-case assumptions.

CRediT authorship contribution statement

Fredrik Andersson: Writing – review & editing, Validation, Software, Resources, Methodology, Formal analysis, Data curation. **Simon Barthelemy:** Writing – review & editing, Validation, Software, Resources, Methodology, Data curation. **Harald Cederlund:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Harald Cederlund reports financial support was provided by Swedish Transport Administration. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to extend their thanks to Carl Westberg for donating the special mounts that were used to hold the filter papers during the field trials. We would also like to thank *WeedFree on Track*, especially Jonathan Caine, for their collaboration during the trials, assisting us with interpretation of the vegetation coverage datasets, and for answering our many questions about the setup of nozzles and vegetation zones on the herbicide spraying train. Finally, we would like to thank the Swedish Transport Administration (*Trafikverket*) for funding this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.177208.

Data availability

I have attached the data used in the paper as a supplementary file.

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