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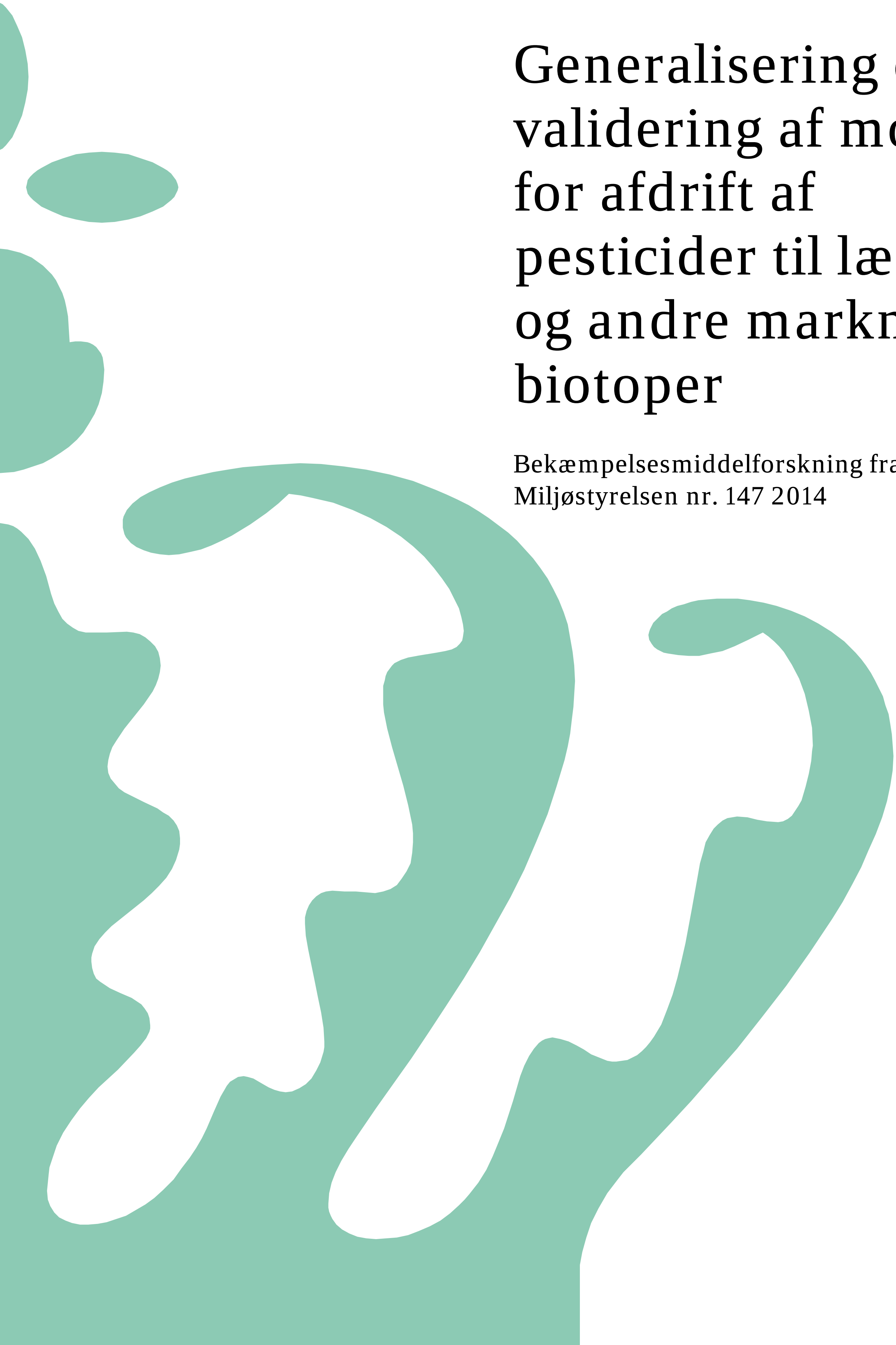

# Generalisering og validering af model for afdrift af pesticider til læhegn og andre marknære biotoper

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**Titel:**

Generalisering og validering af model for afdrift
af pesticider til læhegn og andre marknære
biotoper

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# Indhold

# Forord

I denne rapport beskriver vi resultaterne af det arbejde, der er udført i forbindelse med projektet ”Generalisering og validering af model for afdrift af pesticider til læhegn og andre marknære biotoper”. Projektet er udført af Aarhus Universitet med støtte fra Miljøstyrelsens program for Bekæmpelsesmiddelforskning i perioden 2010-2011.

Ud over forfatterne til denne rapport har følgende AU-medarbejdere bidraget til projektet: Anna Marie Plejdrup, Lise Lauridsen, John Rytter, Trine Guldager Sørensen, Elin Jørgensen, Zdenek Gavor, Morten Strandberg, Bjarne Jensen. Sprøjtningerne blev udført af Sjørslev Maskinstation, og Arne Jørgensen og Inger Kunz har lagt jord til undersøgelserne. Forfatterne ønsker hermed at udtrykke deres tak for de nævntes indsats og velvilje.

Projektet har været fulgt af en følgegruppe bestående af Ilse Ankjær Rasmussen fra ICROFS (Internationalt Center for Forskning i Økologisk Jordbrug og Fødevaresystemer), Poul Henning Petersen og Ghita Cordsen Nielsen fra Videncentret for Landbrug, Henrik Frølich Brødsgaard og Jørn Kirkegaard fra Miljøstyrelsen, Lise Nistrup Jørgensen og Kristian Kristensen fra Aarhus Universitet, Peter Esbjerg og Jens Erik Ørum fra Københavns Universitet, Niels Lindemark fra Dansk Planteværn, Ivar Lund fra Syddansk Universitet og Steen Fogde fra Danmarks Biavlerforening.

# Sammenfatning

I det netop afsluttede projekt "Generalisering og validering af model for sprøjtemiddelafdrift til læhegn og andre marknære biotoper" har vi målt, hvor meget af det sprøjtemiddel, landmanden sprøjter ud, der ender i markens læhegn. Målingerne er anvendt til at videreudvikle og validere en model, der kan forudsige afdriften af de fleste sprøjtemidler under forskellige betingelser. Modellen kan tage hensyn til de givne egenskaber for pesticidet og til dysens dråbestørrelser, hvordan vejret er, og om der er en sprøjtefri zone mellem traktoren og naturen uden for marken.

Idet fokus vedrørende afdrift af pesticider både i Danmark og andre lande primært har været afdrift til vandløb, har arbejdet med at forudsige og modellere størrelsen af afdriften under forskellige forhold været koncentreret om den vandrette afsætning af sprøjtemiddel, dvs. afsætningen i 0 m højde. Imidlertid har flere undersøgelser vist, at også bærproducerende buske og træer som fx fuglekirsebær, tjørn, seljerøn og hyld er følsomme for selv små doser af visse herbicider. Det betyder, at afdrift af herbicider til fx læhegn kan resultere i en mindre blomstring og bærsætning, hvilket kan have betydning fx for de fugle, der lever af bærrene i vinterperioden, og de bestøvende insekter, der er afhængige af en kontinuert tilgang til blomster. Tilsvarende ved vi fra andre undersøgelser, at de blomstrende planter i hegnenes fodpose kan påvirkes af lave herbiciddoser. Vi har derfor ønsket at etablere en model, som kan forudsige afdriften af pesticider til terrestriske habitater, inklusive dem med en vertikal udstrækning som fx læhegn.

Undersøgelsen bygger videre på det arbejde, der startede i projektet "Vurdering af omfang og effekt af afdrift af ukrudtsmidler til danske læhegn eksemplificeret ved metsulfuron", og har dermed haft til formål dels at indsamle data for afdrift ved brug af andet sprøjteudstyr og andre sprøjte-indstillinger med henblik på at gøre afdriftsmodellen mere generelt anvendelig, dels at validere modellens evne til at forudsige sprøjtemiddel-afdrift.

I juni 2010 sprøjtede vi to gange en mark med et farvestof. Sprøjtningen blev udført med en liftophængt sprøjte med påmonterede luftinjektionsdyser, der begrænser afdriften af pesticid til markens omgivelse, primært ved at producere større dråber end konventionelle dyser, idet store dråber afsættes hurtigere i afgrøden end mindre dråber. Vi målte afsætningen af farvestof på blandt andet træernes blade og curlere, idet curlere er et mere ensartet opsamlingsmedie. Ved at indsamle prøver i forskellig afstand til sprøjten og i forskellig højde fik vi data, som udtrykker afsætningen fra denne type dyse, og som kan sammenlignes med tidligere indsamlede data for konventionelle dyser. Desuden er data anvendt til at videreudvikle og validere afdrifts-modellen mht. forudsigelse af afdriften fra forskellige typer hydrauliske dyser. Derudover er de indsamlede data sammen med data fra projektet "Vurdering af omfang og effekt af afdrift af ukrudtsmidler til danske læhegn eksemplificeret ved metsulfuron" og data fra litteraturen brugt til at tilpasse afdriftsmodellen til at kunne beregne effekten af det tryk, dyserne arbejder med, sprøjtebommens højde over afgrøden og sprøjtemidlernes damptryk. I forbindelse med denne tilpasning blev dråbestørrelsessammensætningen af dyserne analyseret for at få så realistisk et udgangspunkt for modellen som muligt.

Efterfølgende er modellen anvendt til at beregne sprøjtemiddelafdriften til læhegn og vandrette flader ved anvendelse af forskellige dysetyper, nemlig en konventionel fladsprede-dyse (Hardi 4110-16) og en almindelig luftinjektions-dyse (TeeJet AI 110-04). Afdriften ved varierende dysetryk er ligeledes beregnet, og forskellen mellem pesticider med forskelligt damptryk er vurderet. Desuden er afdriften ved sprøjtning i forskellig bomhøjder beregnet, ligesom betydningen af vindhastighed, temperatur og relativ luftfugtighed er beregnet. Endelig er betydningen af en sprøjtefri bufferzone for afdriften til såvel læhegn som vandrette arealer uden for marken estimeret.

## 1.1 Hovedkonklusioner

Som forventet var afdriften mindre ved brug af luftinjektions-dysen end ved de tidligere målinger ved sprøjtning med fladsprede-dyse i den samme mark og målinger i de samme læhegn.

Afdriftsmodellen er nu udviklet til at kunne forudsige afdriften ved brug af de fleste typer af sprøjtemidler og forskellige typer hydrauliske dyser under forskellige meteorologiske forhold og ved forskellige indstillinger af sprøjteudstyret.

I forhold til det tidligere projekt tager modellen nu hensyn til, at dråbernes forskellige faldhastigheder også har betydning for afsætningen i selve sprøjtesporet, hvilket har forbedret modellens forudsigelse af afdriften.

Modellen vil kunne anvendes administrativt, hvis der skabes et bruger-interface.

Forskellen i afdrift til læhegn mellem de to typer af dyser viser, at der er potentiale for, via valg af sprøjteudstyr, at reducere mængden af pesticider, der lander i læhegnene og dermed reducerer blomstring og frugtsætning.

Samtidig viser såvel målinger som modelberegninger, at der ikke er den store effekt af sprøjtefrie bufferzoner på afdriften til læhegn, specielt ikke i den øverste del af læhegnene, hvor frugterne ofte er mest talrige.

Modelberegningerne vil også kunne anvendes til at nuancere fx afstandskravene ved sprøjtning langs vandløb og andre typer natur ved anvendelse af forskellige typer sprøjteudstyr og under forskellige sprøjtebetingelser.

# Summary

In the recently completed project ”Generalization and validation of a model for spray drift in hedges and other biotopes near to fields”, we measured how much of the farmer’s pesticide spray ends up in the hedgerow adjacent to the field. The measurements have been used to validate a model that can be used to predict spray drift from most pesticides applied under various conditions. The model takes into account the pesticide’s given properties, the nozzle droplet size, weather conditions and whether a spray free zone has been established between the tractor and nature bordering the field.

As the focus in Denmark and other countries has primarily been on drift to streams, predicting and modeling the extent of drift under varying conditions has been centered on horizontal spray deposition, i.e. deposition at a height of 0 m. However, several studies have shown that berry producing bushes and trees, e.g. bird cherry, hawthorn, Swedish white beam and elder, are sensitive to even small dosages of certain herbicides. This means that drift from herbicides to e.g. hedgerows may result in reduced numbers of flowers and berries, which may have an impact on e.g. birds that feed off the berries during winter and pollinators that depend on continuous access to flowers. Similarly, we know from other studies that flowering plants in the hedgerow bottom may be affected by low dosages of herbicide. We therefore wanted to establish a model that can predict the drift of pesticides to terrestrial habitats, including those that grow vertically, such as hedgerows.

The study continues the work started in the project ”Assessment of extent and impact of herbicide spray drift on Danish hedgerows, exemplified by metsulfuron”, and the purpose has thus been partly to collect data on spray drift from other spray equipment and spray settings in order to make the model more applicable in general, partly to validate the model’s ability to predict spray drift.

In June, 2010, we sprayed a field twice with a dye marker. Spraying was performed with a sprayer mounted with air injection nozzles that limit pesticide drift to the areas surrounding the field primarily by producing larger droplets than conventional nozzles, as larger droplets are deposited faster in crops than smaller droplets. We measured the deposition of dye on tree leaves and hair curlers, as curlers constitute a more uniform collection medium. By collecting samples at varying height and distance from the sprayer, we obtained data that reflects the drift from this kind of nozzle and can be compared to previously collected data on conventional nozzles. In addition, the data is used to further develop and validate the drift model for predicting drift from various types of hydraulic nozzles. Also, the collected data along with data from the project “Assessment of extent and impact of herbicide spray drift on Danish hedgerows, exemplified by metsulfuron” and data from the literature are used to adjust the drift model to calculate the effect of nozzles pressure, the distance of the spray boom to the crops and the vapor pressure of the pesticides. In connection with this adjustment, nozzle droplet size was analyzed in order to make the basis for the model as realistic as possible.

Subsequently, the model has been used to calculate pesticide drift into hedgerows and horizontal surfaces when applying different types of nozzles, i.e. a conventional flat fan nozzle (Hardi 4110-16) and an air injection nozzle (TeeJet AI 110-04). Spray drift at varying nozzle pressure was also calculated and the difference between different pesticides with varying vapor pressure was evaluated. In addition, spray drift from spraying at varying boom height was calculated as was the importance of wind speed, temperature and relative humidity. Finally, the effect of a spray free buffer zone on drift to hedgerows and horizontal surfaces outside the field was calculated.

## 1.2 Main conclusions

As expected, spray drift was reduced when using the air injection nozzle compared to previous measurements using a flat fan nozzle on the same filed with the same hedgerows.

The drift model has now been expanded so that it is able to predict drift when using most pesticides and various types of hydraulic nozzles under varying meteorological conditions at different settings of the spraying equipment.

As opposed to the previous project, the model now takes into account the fact that the droplets' different falling velocities also influence the deposition in the spray track, and this has improved the model's ability to predict spray drift.

The model could be applied administratively if a user interface is created.

The difference in spray drift into hedgerows from applying the two types of nozzles shows that it may be possible to reduce the amount of pesticide that ends up in the hedgerow and affect flowering and fruit set, by choosing the proper spraying equipment.

At the same time, measurements and model calculations show that spray free buffer zones do not have a major impact on spray drift into hedgerows, especially not in the upper part, where fruits are most abundant.

Model calculations can also be used e.g. to refine distance requirements for spraying along streams and other types of landscapes when using different types of spraying equipment under varying spraying conditions.

# 2. Baggrund

Sprøjtemiddelafsætning i hegn og andre marknære biotoper bestemmes af mange forskellige forhold såsom højde af bom, dysetype, sprøjtetryk, afstand til sprøjten, antal sprøjtespor (dvs. bredden af den sprøjtede zone) og meteorologiske forhold (Gilbert og Bell 1988, Nordby og Skuterud 1975, Murphy et al. 2000,Yates et al. 1978, Davis et al. 1994,Goering og Butler 1975). Tidligere undersøgelser (fx Bruus et al. 2008) har desuden vist, at der er stor forskel på afsætningen i vegetation af forskellig højde, og at tiltag, der skal reducere afdriften af sprøjtemiddel, ikke altid har lige god effekt i forskellig højde. Fx vil en sprøjtefri randzone ikke nødvendigvis gavne læhegn og de dertil knyttede organismer.

Der er i det tidligere projekt ”Vurdering af omfang og effekt af afdrift af ukrudtsmidler til danske læhegn” (Bruus et al. 2008) opstillet en afsætningsmodel, der ud fra betingelserne under en sprøjtehændelse kan estimere den afsatte mængde af metsulfuron-metyl og andre sprøjtemidler med lavt damptryk i tjørnehegn.

Afdriftsmodellen forudsiger afsætning på emner i en given højde og i en given afstand fra sprøjten. En af svaghederne i afdriftsmodellen har været, at den initielle afdrift (den del af sprayen som ikke afsættes i selve sprøjtesporet) er empirisk bestemt alene ud fra vindhastigheden og luftens turbulens uden hensyn til dysens karakteristika. Den initielle afdrift afhænger imidlertid også af dråbernes størrelse således, at afdriften er størst for de mindste dråber. Vi har derfor ønsket at forbedre afdriftsmodellens realisme ved at tage hensyn til dette.

På basis af det netop afsluttede projekt ”Vurdering af omfang og effekt af afdrift af ukrudtsmidler til danske læhegn” (Bruus et al. 2008) kunne vi konkludere, at de estimater for afdrift, der for nuværende anvendes i forbindelse med risikovurdering af sprøjtemidler, ikke i tilstrækkelig grad tager hensyn til eksponeringen af marknære naturarealer med en vertikal udstrækning, fx læhegn. Modelleringen af afdriften viste nemlig, at flere sprøjtespor bidrager relativt mere til afsætningen af herbicid i hegnstræer, end tilfældet er for afsætningen i lav vegetation såsom hegnenes fodposer. Således er afdriften i 4 m højde op til 30 gange så stor, når bidraget fra en sprøjtezone på 120 m summeres (i dette tilfælde 10 sprøjtespor), som bidraget fra 12 m (sprøjtesporet nærmest hegnet) ved en sprøjtning uden sprøjtefri randzone. I ½ m højde er der ikke nær så store forskelle (ca. 1,3 gange så meget afdrift fra 120 m som fra 12 m). Idet den modelberegnede afdrift kan omsættes til afsætning i hegnet, har det været muligt at sammenligne modelberegningerne med tidligere undersøgelser. Gilbert & Bell (1988), Nordby & Skuterud (1975) og Yates et al. (1978) fandt, at der maksimalt blev afsat 3,4-10 gange så meget fra 10 spor (70-120 m) som fra et spor, og dermed er der nogenlunde overensstemmelse mellem modelberegningerne og disse undersøgelser. Vores tidligere undersøgelse bekræfter således, at der ved vurdering af afdrift fra marksprøjtning bør medtage bidragene fra mindst 120 m. Dette er endnu vigtigere ved vurdering af afdriften til hegn ved etablering af sprøjtefrie bufferzoner, idet det relative bidrag fra de fjernere sprøjtespor øges, når bredden af bufferzonen øges. Det har derfor været relevant at medregne bidraget fra en endnu bredere sprøjtezone.

Modellen er tidligere valideret mht. til forudsigelse af afsætningen i tjørn ved sprøjtning med dysetypen Hardi 4110-16 (konventionel dyse) ud fra oplysninger om den dysespecifikke dråbestørrelsesfordeling for en næsten tilsvarende dyse (XR 11002). Endvidere har modellen været anvendt til at beregne af drift ved brug af en afdriftsreducerende dyse (TeeJet AI 11004). En validering af modellen i forhold til den afdriftsreducerende dyse har været ønsket om at underbygge modellens anvendelighed yderligere. Tilsvarende var en gentagen validering på baggrund af de eksisterende data for den konventionelle dyse, men med nye oplysninger om den dysespecifikke dråbestørrelsesfordeling for præcis den anvendte dyse påkrævet. Med sådanne undersøgelser vil man i højere grad være i stand til kvalificeret at sammenligne effekten af forskellige afdriftsregulerende tiltag som fx sprøjtefrie randzoner og afdriftsreducerende sprøjteudstyr og -indstillinger.

Mange pesticider vil fordampe under afdrift, jf. http://www.eu-footprint.org/ppdb.html. De hidtidige modelberegninger blev gennemført under antagelse af, at det anvendte pesticid ikke fordamper fra dråberne, dvs. stoffet har et meget lavt damptryk. Vi har derfor ønsket at indarbejde pesticidets damptryk i modellens dråbemodul, og ved hjælp af afdriftsmodellenat undersøge, hvilken indflydelse damptrykket har for udviklingen i koncentrationen i dråberne under transporten væk fra sprøjten og dermed i afsætningen af pesticid på planter.

I de tidligere undersøgelser af afdrift af metsulfuron-metyl (Bruus et al. 2008) blev der kun i ringe udstrækning målt afsætning til vandrette flader, idet formålet med undersøgelserne var at studere afsætning i læhegn. Det har imidlertid været væsentligt, at sådanne målinger udføres med henblik på validering af modellens forudsigelser af afsætning i lav vegetation og på vandrette flader. Desuden kan disse målinger indgå i massebalance-betragtningerne i forbindelse med valideringen af modellens forudsigelse af, hvor stor en andel af pesticidet afsættes vandret, og hvor stor en del driver med vinden.

Formålet med projektet har således været at øge anvendeligheden af en allerede opbygget afdriftsmodel (Bruus et al. 2008) således, at modellen kan bruges som et ressourcebesparende værktøj til at vurdere eksponeringen af marknære biotoper for afdrift af sprøjtemidler. Modellen vil ikke i forbindelse med dette projekt blive offentlig tilgængelig, men vil kunne udvikles til at blive anvendt af personer med almindelig computererfaring og en smule landbrugsfaglig indsigt i forbindelse med rådgivning, i undervisning og eventuelt regulering af pesticidanvendelsen.

# 3. Materialer og metoder

I projektet er udført forsøg og målinger, der har genereret data for afsætning af sprøjtemiddel vandret og lodret samt de aktuelle meteorologiske forhold, som bruges til dels at validere den tidligere opstillede afdriftsmodel, dels at udvide modellens anvendelsesområde til også at omfatte afsætning af pesticider på vandrette flader, afdrift af fordampende stoffer og en bredere sprøjtezone (flere sprøjtespor). De konkrete indsamlinger af data er nærmere beskrevet nedenfor samt i Bilag 1 og Bilag 2.

## 3.1 Rapportens opbygning

Der er gennemført to sprøjtninger med luftinjektionsdyse. Ved disse sprøjtninger er indsamlet mål for afsætning i forskellig afstand til sprøjten og i forskellig højde. Data fra disse sprøjtninger indgår sammen med eksisterende data fra det afsluttede projekt " Vurdering af omfang og effekt af afdrift af ukrudtsmidler til danske læhegn eksemplificeret ved metsulfuron" (Bruus et al. 2008) i artiklen "Pesticide deposition due to spray drift into hedgerows from multiple spray swaths" (Bilag 1, Kjær et al. 2014), i hvilken der findes en nærmere beskrivelse af de udførte forsøg. Desuden er data fra begge projekter anvendt til opbygning og validering af en model, der kan forudsige afdriften af sprøjtemidler med alle relevante damptryk til læhegn ved anvendelse af forskelligt sprøjteudstyr, forskellige indstillinger af sprøjteudstyret, varierende meteorologiske forhold og varierende afstand. Denne model og forskellige scenarieoutput er præsenteret i artiklen " The OML-SprayDrift model for predicting pesticide drift and deposition from ground boom sprayers" (Bilag 2, Løfstrøm et al. 2013). I kapitel 3 præsenteres resultaterne fra nærværende projekt kort, med henvisninger til de føromtalte artikler/bilag. I kapitel 4 er resultaterne fra nærværende projekt diskuteret sammen med andre relevante studier, herunder Bruus et al. (2008). Kapitel 5 opsummerer konklusionerne fra nærværende projekt, og kapitel 6 præsenterer nogle forskningsmæssige og administrative perspektiver.

## 3.2 Princippet bag afdriftsmodellen

Det generelle princip i den udviklede afdriftsmodel (Bruus et al. 2008) bygger på sammenbygningen af en dråbemodel og en spredningsmodel. Dråbemodellen beskriver som det centrale, en dråbes størrelse og faldhastighed, som er afgørende for afsætningshastigheden til (jord-)overfladen. Spredningsmodellen beskriver spredning, fortynding og afsætning af en udsendt 'sky' af dråber.

Når en dråbe forlader en dyse på en sprøjtebom, begynder den straks at fordampe og blive mindre under transporten mod overfladen. Store dråber vil umiddelbart falde til jorden uden nævneværdig ændring af størrelse; men jo mindre dråben er, jo større er sandsynligheden for, at dråben 'fanges' af (middel-)vinden og turbulente hvirvler, hvilket betyder at opholdstiden i luften forøges betydeligt, og at dråben begynder at mindskes og dermed også mindske faldhastighed.

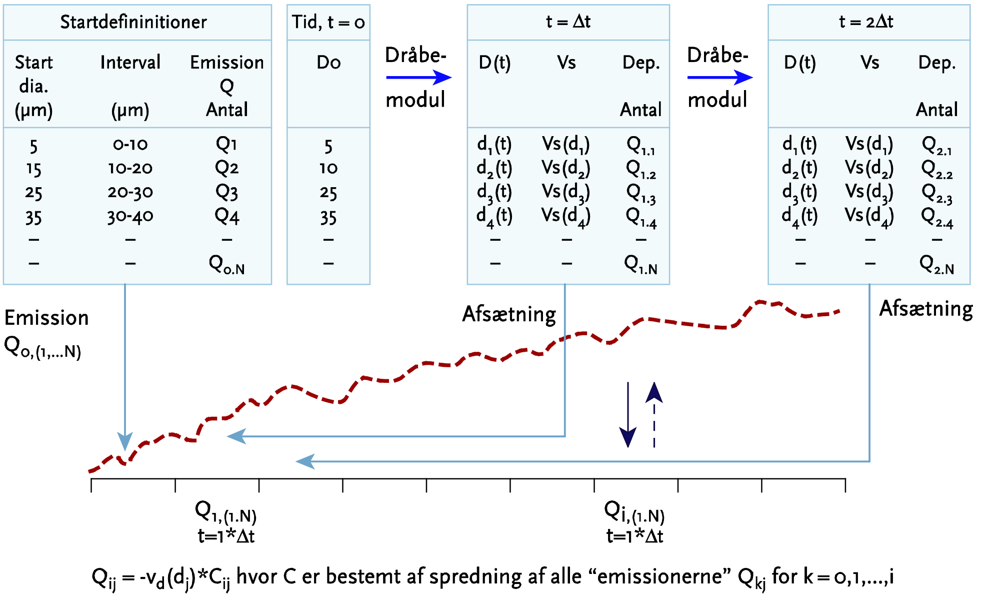
Den udviklede afdriftsmodel tager udgangspunkt i en dråbestørrelsesfordeling bestemt af tabelværdier for den anvendte dyse samt den udsprøjtede mængde væske og herbicid pr. arealenhed. Den andel, der ikke umiddelbart afsættes i det kørte sprøjtespor, men føres videre med vinden, betegnes "initiel afdrift" og er omtrent proportional med vindhastigheden. Dråbestørrelsesfordelingen er i modellen repræsenteret ved et endeligt antal diameterintervaller à 10 µm, hvor egenskaberne for en dråbe med den centrale værdi beskriver hele intervallet. Beregningen foregår for et sprøjtespor ad gangen, og bidrag fra et givet antal spor adderes.

For et sprøjtespor beregnes fordampning og afsætning til (jord-)overfladen i skridt henover små arealelementer nedstrøms for sporet. Ved hvert skridt beregnes dråbernes nye diameter (efter fordampning) og nye faldhastighed, som bestemmer afsætningshastigheden til (jord-)overfladen. Princippet er skitseret i Figur 2.1.

Dråbemodellen beskriver udviklingen af en dråbes størrelse og faldhastighed, efter den har forladt en dyse. Modellen tager hensyn til udgangshastigheden på dysen, luftens fugtighed og temperatur. Modellen tager også hensyn til at dråberne indeholder opløste stoffer (fx pesticider). Hvis dråberne opholder sig tilstrækkelig lang tid i luften, vil de til sidst fordampe til en mindste størrelse, hvor det opløste stof 'holder' på det sidste vand. Slutdiameteren afhænger af startkoncentrationen af det opløste stof.

Spredningsmodellen kan umiddelbart håndtere spredning og afsætning af en dråbe, som har en konstant faldhastighed. Når en dråbe under transporten med vinden ændrer diameter, vil afsætningshastigheden også ændres. Det tager afdriftsmodellen hensyn til ved at koble dråbemodellen på som et modul i spredningsmodellen. Spredningsmodellen beregner spredningen af afdriftsfanen i trin væk fra sprøjtezonen, og for hvert trin anvendes dråbemodellen til at beregne en aktuel dråbestørrelse og faldhastighed på basis af transporttiden, inden afsætningshastigheden og dermed afsætningen beregnes. Dette princip anvendes for alle dråber, som grupperes i størrelsesklasser á 10 µm i forhold til startdiameteren.

Afdriftsmodellen kan herved bestemme en koncentration af en given dråbestørrelse i en vilkårlig afstand til sprøjtesporet og i vilkårlig højde over jorden. Hver dråbe har fra starten den samme koncentration uanset størrelsen, og dermed et givet stofindhold. Selv om dråberne bliver mindre under transporten, vil de stadig indeholde den samme stofmængde, som ved start, idet de anvendte stoffer har meget lavt damptryk. Derfor kan modellen i et givet punkt beregne den samlede stofmængde pr. $m^3$ (eventuelt for et interval af størrelser) ved at summere over dråbestørrelsernes stofmængde og deres antal.
Modellen tager ikke hensyn til dråbernes indbyrdes dråbepåvirkninger, dråbesammenfald i sprayen. Dråbesammenfald vil betyde lidt flere større dråber (på bekostning af små dråber), hvilket i beregningerne vil give en lidt for lav afsætning til overfladen og lidt for stor afdrift. Disse effekter er af sekundær betydning og størrelsen af manglen/fejlen fremgår af at målinger og beregninger stemmer godt overens.



FIGUR 3.1. SKEMATISK FREMSTILLING AF AFDRIFTSMODELLEN, SOM SAMMENKOBLER DRÅBEMODELLEN OG SPREDNINGS- OG AFSÆTNINGSMODELLEN OML-DEP. FOR EN VIND FRA VENSTRE MOD HØJRE BEVÆGER MODELLEN SIG I TRIN (ΔT) VÆK FRA SPRØJTESPORET MED EN EMISSION Q0,1..N, HVOR INDEKS 0 REFERERER TIL AREALET INKLUDERET I FØRSTE TRIN OG 1.N TIL KLASSER FOR INITIELLE DRÅBESTØRRELSER, D0. I NÆSTE TRIN VÆK FRA SPRØJTESPORET ER DER FORLØBET EN TID T. MED DRÅBEMODELLEN BEREGNES FOR HVER INITIELLE DRÅBESTØRRELSE EN NY DIAMETER DI(T), SOM HAR INDFLYDELSE PÅ AFSÆTNINGSHASTIGHEDEN. SPREDNINGSMODELLEN BESTEMMER DEREFTER FORTYNDINGEN OG EN AFSÆTNING, Q1,1..N, I DETTE TRIN. DENNE AFSÆTNING FRATRÆKKES DEREFTER DEN TILGÆNGELIGE STOFMÆNGDE I DEN VIDERE BEREGNING LÆNGERE VÆK FRA SPRØJTESPORET. VS ER FALDHASTIGHEDEN AF DRÅBER OG VD ER AFSÆTNINGSHASTIGHEDEN, HVOR BEGGE ER FUNKTION AF DIAMETEREN D.

## 3.3 Måling af afdrift

Bortset fra de anvendte dyser er metoderne er stort set identiske med metoderne anvendt i Bruus et al. (2008) af hensyn til muligheden for at anvende gamle og nye data sammen.

I juni 2010 gennemførte vi to sprøjtninger med farvestoffet natriumfluorescein i marken med en luftinjektionsdyse, TeeJet AI 110-04. Forsøgene blev udført i en kornmark med ca. 20 cm høj afgrøde. Afsætningen af sprøjtemiddel i hegn blev bestemt ved sprøjtning i fem sprøjtespor langs et læhegn. Under sprøjtningerne indsamlede vi data, der beskriver sprøjtefanens horisontale og vertikale udbredelse i bevægelse med vinden over flad mark mod hegn samt afsætningen i hegnet. Idet sammenhængen mellem afsætning af farvemarkøren natriumfluorescein og ukrudtsmidler med lavt damptryk (fx metsulfuron) er kendt (Bruus et al. 2008), er der alene sprøjtet med farvestoffet.

Under forsøget målte vi afsætningen i fem højder (0, ½, 1, 2, 4 m) i hegnet. Vi indsamlede prøver fra både blade og curlere placeret i hegnet, samt curlere anbragt på 25 master placeret langs sprøjtesporene (forsøgsopstilling er vist i Figur 2.2). Umiddelbart efter kørsel i hvert overførte vi de indsamlede prøver til lystætte væskebeholdere for at undgå henfald af markøren. Herefter blev den afsatte mængde sprøjtemiddel bestemt ved hjælp af fluorescensspektofotometri (Sharp 1974; Davis et al. 1994).

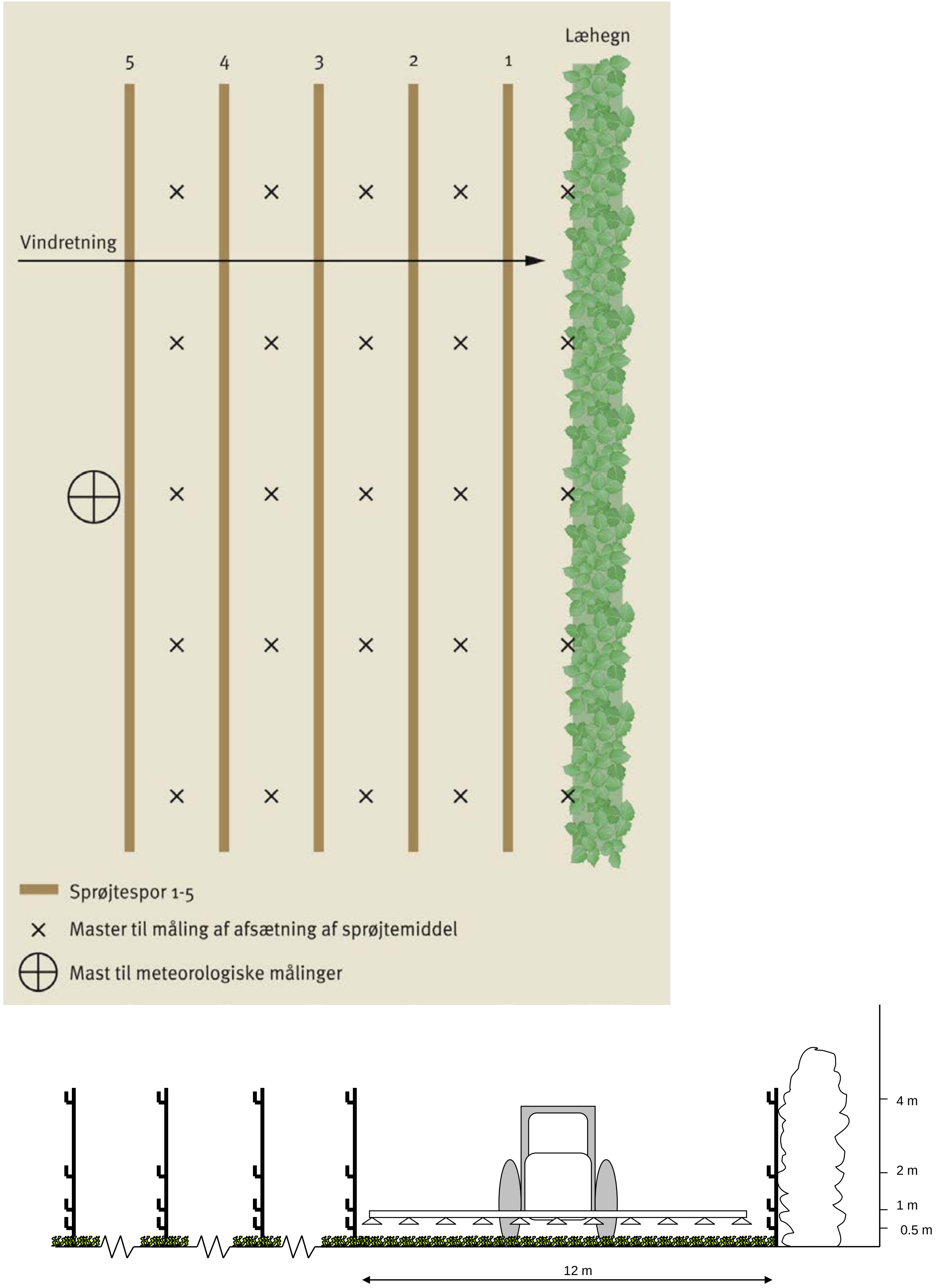
De generelle meteorologiske forhold blev registreret ved hjælp af en meteorologimast opstillet på forsøgsmarken. Masten var monteret med udstyr til at måle temperatur, luftfugtighed, skydække, vindhastighed mm.

## 3.4 Vandret afsætning

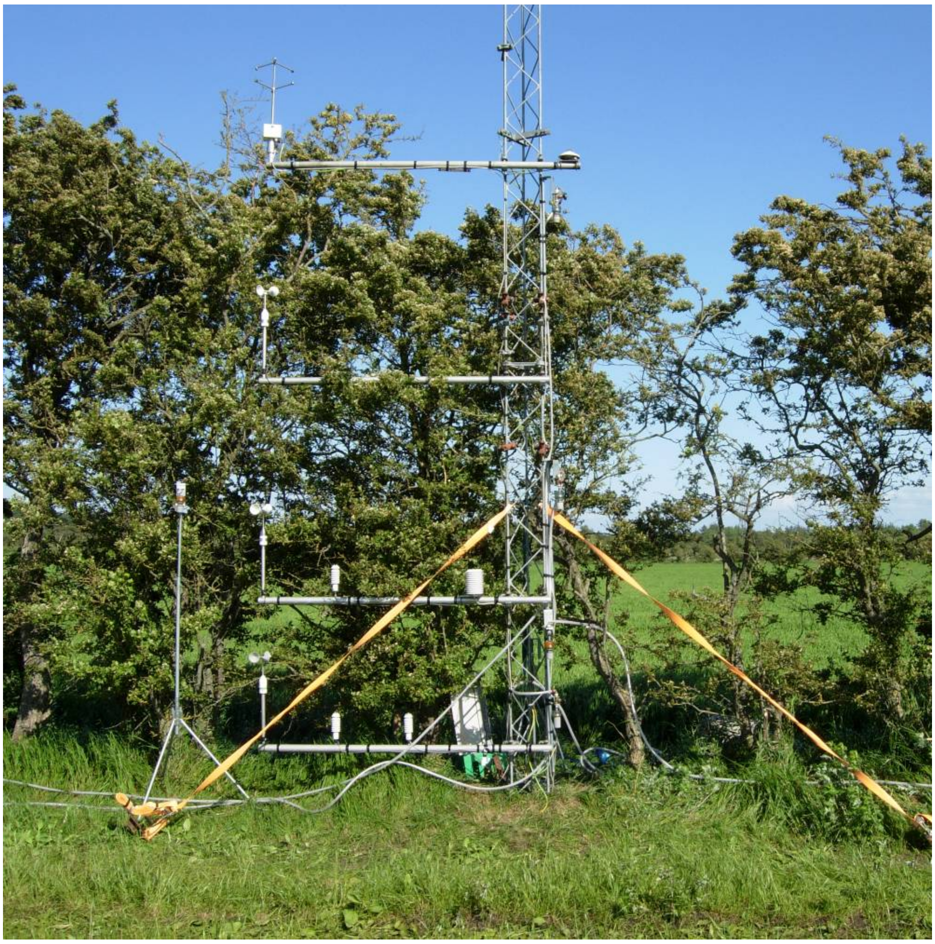
Med henblik på at verificere modellens beregning af deposition og den samlede massebalance målte vi depositionen til vandrette overflader (filterpapir) mellem 1. og 2. række af målemaster i forhold til sprøjtesporet, idet dråbeskyen her stadig befinder sig under den højeste målehøjde, dvs. skyen endnu ikke er opblandet til 4 m. Endvidere er dråberne endnu så store og tunge mellem 1. og 2. sprøjtespor, at deres sedimentation dominerer over den afsætning, der sker med turbulensen. Det betyder, at afsætningen til et vandret papir på overfladen vil være sammenligneligt med afsætningen til en overflade med ringe vegetation. I forhold til massebalancebetragtninger er dråberne også så store mellem 1. og 2. sprøjtespor, at målingerne med curler kvantitativt vil dække det meste af dråbestørrelsesspektret, der passerer horisontalt.

## 3.5 Luftstrømning i gennem og over læhegn

I spraymodellen ligger en antagelse om, at den mængde luft, som strømmer gennem læhegnet i det væsentligste ikke er anderledes end på en tilsvarende vertikal flade på den åbne mark. Det betyder, at den luftmængde, som eventuelt skulle blive presset op over hegnet, er antaget at være af mindre betydning. For at få en lidt bedre viden om antagelsen blev der udført målinger af vinden på marken og i læhegnet, idet en metode til sammenligning af strømningen på marken og i hegnet er at se på vindhastighederne i de forskellige højder og den luftmængde, som strømmer gennem en vertikal flade (den horisontale fluks). Målingerne på marken blev udført med en fritstående mast med et ultrasonic anemometer (herefter kaldet en sonic) i højden 4,3 m. En sekundær meteorologimast opsat umiddelbart foran hegnet med måleinstrument (sonicanemometer) placeret ved toppen af hegnet målte forholdet mellem vertikal og horisontal vindhastighed (Figur 2.3). Masten var anbragt i den tætteste del af hegnet, og målerne var placeret næsten inde i bevoksningen i samme vertikale plan som de yderste grene ca. en meter fra hegnets centerlinje. Den øverste måling var i samme højde som toppen af læhegnet. Vindmålingerne blev suppleret med måling af en vertikal vindprofil lige foran hegnet, således at fluksen af luft (luftmængden) gennem hegnet kunne sammenlignes med forholdene på marken.



FIGUR 3.2. SKEMATISK OVERSIGT OVER FORSØGSOPSTILLINGEN I MARKEN, DELS SET I FUGLEPERSPEKTIV (ØVERST), DELS SET PÅ TVÆRS AF KØRERETNINGEN (NEDERST).



FIGUR 3.3. METEOROLOGISK MAST PLACERET I LÆHEGN. DER SES FIRE TVÆRBOMME MED UDSTYR TIL MÅLING AF BL.A. VINDHASTIGHED. DE TRE NEDERSTE BOMME HAR CUPPER I HØJDERNE 1, 2 OG 3,5 M. SONIC-MÅLEREN, SOM DESUDEN MÅLER TURBULENS, ER PLACERET I 5,1 M, HVILKET SVARER TIL HØJDEN AF HEGNET.

## 3.6 Modeludvikling og validering

Afdriftsmodellens anvendelighed til forudsigelse af afsætning af sprøjtemiddel i læhegn og andre marknære biotoper er blevet øget ved:

- at parametrisere den initielle afdrift ud fra data for den dysespecifikke dråbestørrelsesfordeling af de anvendte dyser og indførelse af en submodel (Tilting Plume), som beskriver de enkelte dråbestørrelsers vertikale nedsynkning inden for sprøjtesporet
- inddrage fordampningen af sprøjtemidler
- udvide den medregnede sprøjtezone (antal sprøjtespor)

Den videreudviklede model anvender en ny metode til beregning af initiel afdrift, det vil sige den del af sprayskyen, som driver væk fra selve sprøjtesporet. Uden for sporet er modellen i princippet som før. Den initielle afdrift blev før beregnet procentvis ens for alle dråbestørrelser og var med god tilnærmelse en lineær funktion af vindhastigheden. Den ny model bygger på det princip, som i litteraturen kaldes 'Tilting Plume', og beregner de enkelte dråbers (dråbeklassers) gennemsnitlige vertikale faldvej i sprøjtesporet og den tilhørende statistiske fordeling af dråber omkring gennemsnitspositionen. De numeriske beregninger foregår i skridt på 1 m mod tidligere 4 m, hvilket forbedrer præcisionen.

### 3.6.1 Dråbespektre for dyser

På grund af, at vi ikke hverken i litteraturen eller ved henvendelse til Hardi kunne få oplysninger om den initielle dråbestørrelsesfordeling for dysen Hardi 4110-16, henvendte vi os til David Nuyttens fra firmaet ILVO i Belgien for at få bestemt dråbestørrelsesfordelingen for både fladsprededysen Hardi 4110-16 (3 og 5,5 bar tryk) og luftinjektionsdysen TeeJet 110-04 (3 bar). Dråbespektrene blev bestem vha. den PDPA laser-baserede målemetode (Nuyttens et al. 2007b & 2009).

### 3.6.2 Initiel afdrift

På grundlag af eksisterende og nye data blev udviklet en ny submodel for den initielle afdrift fra det enkelte sprøjtespor på basis af den målte afdrift på curlerne på masterne og de meteorologiske målinger.
Submodel er baseret på det såkaldte 'Tilting Plume' princip (Craig 2004; Lebeau et al. 2011). I modellen dråberne op delt i diameterklasser a 10 µm repræsenteret ved en diameter midt i intervallet. For hver klasse beregnes de nedsynkende dråbernes højde over jorden og deres vertikale spredning med spredningsmodellens metoder, dog således at dråbefanens centerlinie synker med dråbens hastighed og det fiktivt tillades at dråberne spredes under jordoverfladen. Når skyen når kanten af sprøjtebommen betragtes den andel af dråbeskyen, som befinder sig under jorden, som værende afsat i sporet. Den resterende del er den initielle afdrift (se evt. nærmere i Bilag 2).

I parametriseringen indgår nye data for den dysespecifikke dråbestørrelsesfordeling for dysen Hardi 4110-16, som er anvendt i det tidligere projekt (Bruus et al. 2008).

### 3.6.3 Damptryk for pesticider

Koncentrationen af stof i dråberne er - udover fordampningen af vand - også under indflydelse af eventuel fordampning af pesticidet. Her er damptrykket (fordampningshastigheden) af pesticidet afgørende. Dråbemodulet er blevet udviklet til, ud over vand, også at inddrage fordampning af pesticider. Det har ikke været muligt at inddrage indflydelsen fra tilsætningsstoffer påvirkning af fordampningen (se evt. nærmere i Bilag 2).

### 3.6.4 Sprøjtezonens bredde

Modellen blev udvidet fra at omfatte 10 sprøjtespor (120 m) til at omfatte 20 spor (240 m) ved at udvide modellens beregningsdomæne gennem en udvikling/tilpasning af modelkoden.

### 3.6.5 Validering

De nye præcise målinger af dråbespektre for fladsprede dysen samt det nye beregningsprincip for initiel afdrift gjorde, at der måtte foretages en ny modeltilpasning på grundlag af data fra 2005 (Bruus et al. 2008). På grundlag heraf blev modellen valideret mod de nye data fra 2010 for lavdriftsdysen.

### 3.6.6 Scenarieberegninger

Der er foretaget en række scenarieberegninger, som har til formål at beskrive afdriftsmodellens følsomhed for inputparametrer/set-up-værdier og at belyse virkningerne af forskellige tiltag for at begrænse afdriften. Beregningerne beskriver afdriften og den horisontale afsætning (deposition). Afdriften i form af den horisontale fluks af pesticid (ng $cm^{-2}$) er beregnet i forskellige højder over jorden i kanten af marken. I modsætning til kalibrering og validering af modellen, hvor kun dråbestørrelser over 10 µm indgik, indgår alle dråbestørrelser i scenarieberegningerne.

Rækken af inputparametre til beregningerne er listet nedenfor.

- Nominel marktilførsel af metsulfuron-methyl: 4 g/ha= 400 ug/$m^2$, damptryk 7,7 mPa
- Væskemængde: 300 l/ha; svarende til tankkoncentration på 0,0133 g/l
- Sprøjtebommens højde over afgrøden: 0,5 m

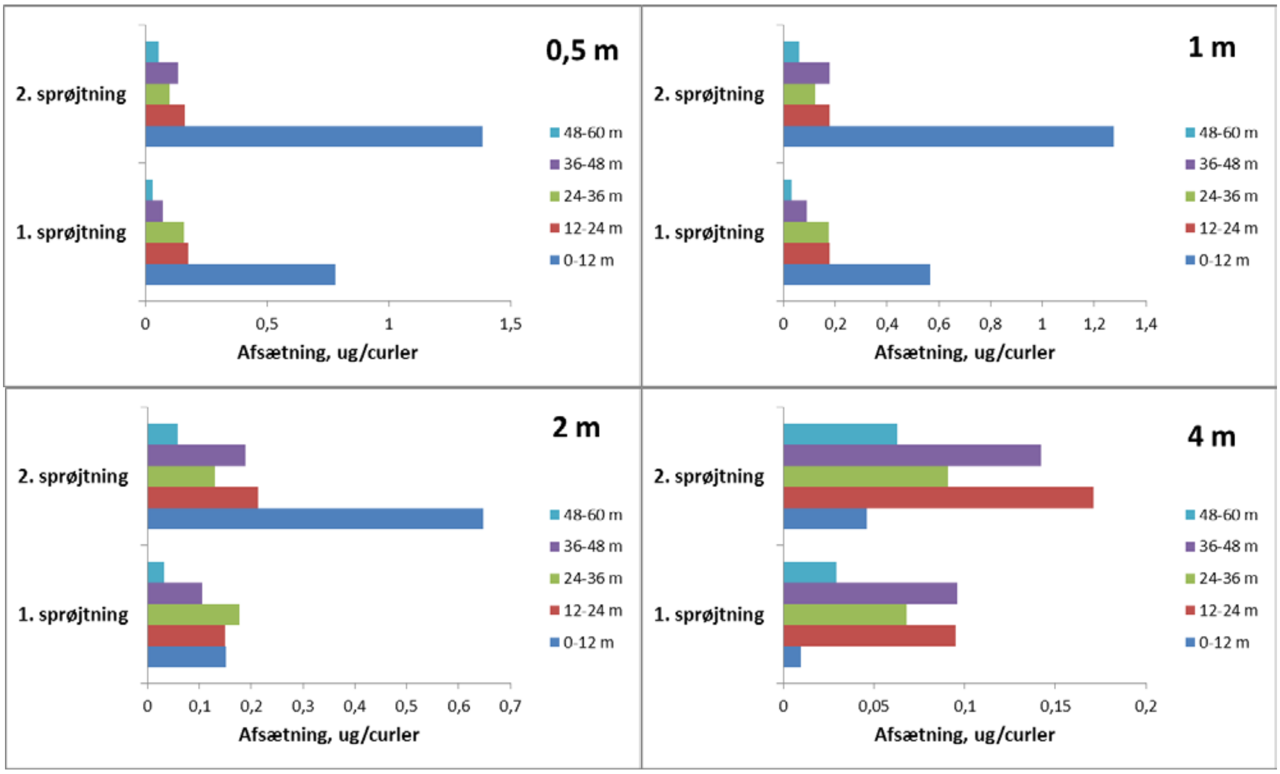
- Dysetryk: 3 atm.
- Dysetype: TeeJet AI 11004
- Vindhastighed: 4 m/s i 4 m højde
- Vindretning vinkelret på markkant
- Relativ fugtighed: 60 %
- Lufttemperatur: 15 °C
- Varme fluks: 100 W/m$^2$
- Aerodynamisk ruhed: 0,1 m
- Bredde af mark: 240 m
- Bredde af bufferzone: 0 m

I hvert scenarie er der kun varieret på én af parametrene, og de øvrige er holdt konstante.

# 4. Resultater

## 4.1 Afdrift til læhegn

Som forventet varierede afsætningen med såvel afstanden fra sprøjten som højden i hegnet (Figur 3.1). Desuden varierede afsætningen noget mellem de to sprøjtninger. Det er værd at bemærke, at jo højere i læhegnet man måler, desto mindre forskel er der på afdriften i forskellig afstand fra hegnet. Resultaterne er nærmere beskrevet i Bilag 1.

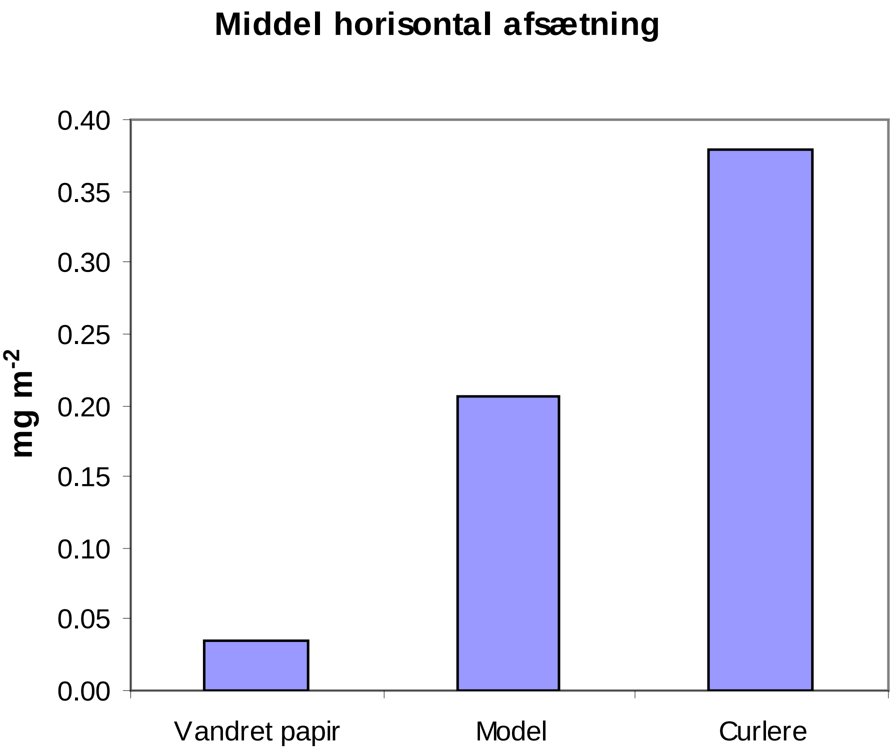


FIGUR 4.1. AFSÆTNING AF NATRIUMFLUORESCEIN PÅ CURLERE I FORSKELLIG HØJDE (0,5-4 M) I LÆHEGN FRA DE 5 SPRØJTESPOR À 12 M BREDDE VED DE 2 SPRØJTNINGER MED TEEJET AI 4110-04 I 2010.

## 4.2 Vandret afsætning

Den vandrette afsætning målt på filterpapir er vist i Figur 3.2. Ud over disse direkte målinger af den vandrette afsætning, er en indirekte måling af den horisontale afsætning mellem masterne i 0 m og 12 m foretaget via den curler-målte forskel i afdriften mellem masterne i 0 m og 12 m. Da kun ubetydelige mængder af sprayskyen var over 4 m medfører en antagelse af massebalance, at forskellen i fluksen mellem masterne vil svare til den horisontale afsætning. Ved beregning af den samlede horisontale afdrift/fluks ved en masterne er målingerne i højderne 0- 0,5-1-2 og 4 m vægtet med 0,25- 0,5,-0,75- 1,5 og 2.

De direkte målinger på filterpapir og de indirekte målinger via curlere er sammenlignet med modelberegninger i Figur 3.2. Da meteorologien kun varierede lidt i 2010, er afsætningen midlet over alle sprøjtningerne. Da afsætningen mellem masterne ikke aftager lineært, repræsenterer den målte deposition i 6 m ikke et gennemsnit for hele området 0-12 m præcist; i følge modelberegningerne modtager hele området i gennemsnit 38 % mere per $m^2$ end depositionen i 6 m.



FIGUR 4.2 GENNEMSNITLIG AFSÆTNING TIL HORISONTAL FLADE (MG $M^{-2}$) I AFSTANDEN 0 TIL 12 M BESTEMT VED DIREKTE MÅLINGER PÅ VANDRET PAPIR 6 M FRA SPRØJTESPOR, VED INDIREKTE MÅLINGER VIA CURLERE AF FORSKELLE I HORISONTAL FLUKS MELLEM MASTER OG MODELBEREGNING. DATA FOR ET SPRØJTESPOR VED 300 L/HA OG NORMERET TIL TANKKONCENTRATION PÅ 1,63 G/L.

## 4.3 Luftstrømning igennem og over læhegn

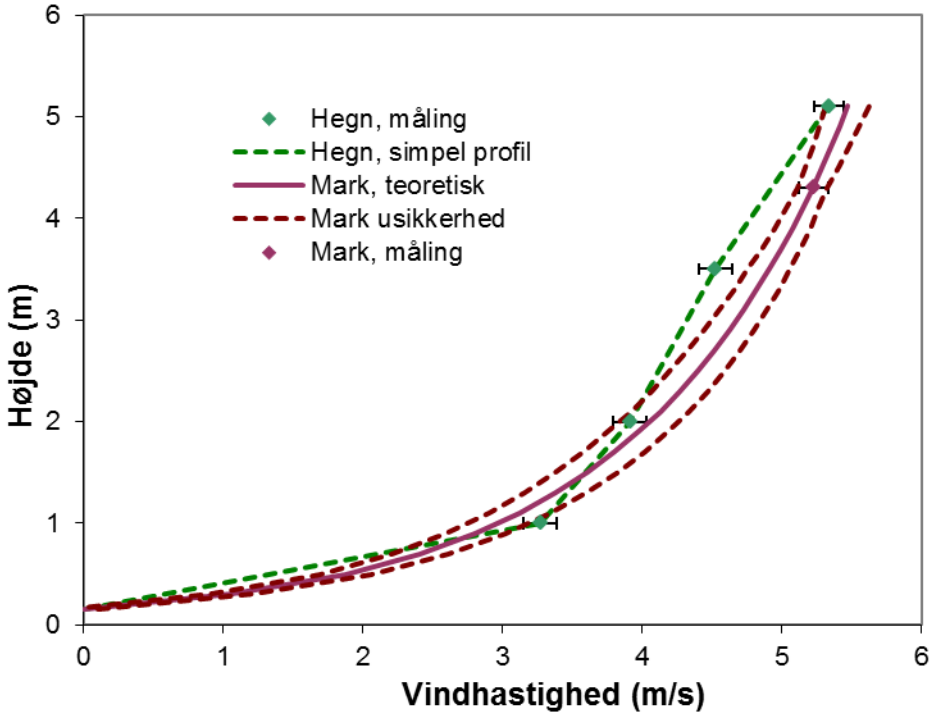
### 4.3.1 Vindhastighed

Da der på marken kun blev målt i en højde, var der nødvendigt at anvende en teoretisk beskrivelse af den vertikale vindprofil. Teorierne for vindprofiler tæt ved jorden (<30m) er velkendte. Vindhastighedens, *u*, variation med højden over jorden, *z*, kan beskrives med følgende funktion:

$$u(z) = \frac{u_*}{\kappa}\left(\ln\left(\frac{z}{z_0}\right) + \psi\left(\frac{z}{L}\right) - \psi\left(\frac{z_0}{L}\right)\right) \qquad (1)$$

hvor $u_*$ er den såkaldte friktionshastighed, $\kappa$ er 0,35, $z_0$ er den aerodynamiske overfladeruhed og L er Monin-Ubukhov længden, som beskriver atmosfæriske de stabilitetsforhold. For neutrale stabilitetsforhold er stabilitetskorrektionen, $\psi$ (fx Panofsky et al 1984), nul, og vindprofilen beskrives med den naturlige logaritmefunktion. For større vindhastigheder har stabiliteten mindre betydning og kan med god tilnærmelse beskrives med neutrale forhold. Under forsøgene udgør korrektionen ca.3 %.

Det teoretiske profil kan bestemmes på to måder. Sonic måler værdien af u* og u(z) direkte, hvorved z0 kan bestemmes. Herved kan vindprofilen fastlægges. I Figur 3.3 er vist vindhastigheden på marken målt med sonic og den tilhørende teoretiske profil for ca. 9 timer på forsøgsdagen. Vindhastighederne målt i læhegnet er også vist.



FIGUR 4.3 VINDHASTIGHEDER (MIDDELVÆRDIER) PÅ MARK OG I LÆHEGN FOR PERIODEN MED FELTFORSØG D.14. JUNI 2010 KL. 8:30 TIL 17:45 (SOMMERTID). PUNKTERNE ER MÅLINGER OG DEN RØDE KURVE ER DEN TEORETISKE PROFIL FOR MARKEN (SE TEKST). USIKKERHED PÅ MÅLINGER ER 0,12 M/S FOR CUPPER I 1, 2 OG 3,5 M OG 2 % FOR SONICMÅLINGERNE. SE TEKST FOR USIKKERHEDEN PÅ DEN TEORETISKE MARKPROFIL.

Usikkerheden på målingerne var for cupper 0,12 m/s (1 σ) og for sonic 2 %. For den teoretiske markprofil vurderedes usikkerheden - udover de 2 % i målehøjden - til at have yderligere 0-5 % usikkerhed, som vokser lineært med afstanden fra sonicen således, at dette usikkerhedsbidrag stiger fra 0 % til 5 % ved jorden. Disse usikkerhedskurver er også vist i Figur 3.3.

I forhold til den teoretiske vindprofil på marken afviger vindhastigheden i læhegnet relativt mest i 1 m og 3,5 m. I 3,5 m er hastigheden klart mindre end teorien, og i 1 m er hastigheden tilsyneladende større. Dette skyldes sandsynligvis læhegnets ujævne tæthed (se evt. Figur 2.3), idet tætheden i 3,5 m er relativt større, hvilket kan forklare dem lidt mindre hastighed en forventet. Modsat er hegnet lidt mere åbent i bunden, hvilket giver lidt større hastighed. Den generelle tendens er dog, at hastigheden er lidt lavere i læhegnet.

### 4.3.2 Horisontal fluks

Den luftmængde, som strømmer gennem en vertikal flade (den horisontale fluks), kan estimeres ved at bestemme arealet mellem kurverne i Figur 3.3 og y-aksen. Den horisontale fluks af luft mellem 0 m og 5,1 m beregnes derfor således ved at integrere (1):

$$Fluks = \int_{z0}^{5,1} u(z)\, dz$$

Når kurven for marken i figuren integreres fås værdien 20,3±0,9 $m^3$/s/m.

For læhegnet er fluksen beregnet ved et simpelt numerisk integral for læhegnet (arealet mellem den stiplede grønne linie og y-aksen). Fluksen bliver 19,2 $m^3$/s/m og er således ca. 1,1 $m^3$/s/m eller 5 % mindre end den tilsvarende på marken. Usikkerheden på den numeriske integration er dog relativt stor, når der kun indgår fire målepunkter, og usikkerheden er formodentlig af samme størrelse som forskellen i fluksene. Beregningerne indikerer, at en mindre mængde luft tvinges op over hegnet; det vil sige en vertikal fluks omkring læhegnet på ca. 1,1 $m^3$/s/m.

### 4.3.3 Vertikalhastighed i hegn

Sonicen målte også den vertikale komponent af vindhastigheden. På marken var der ingen vertikal komponent, idet marken er horisontal. I læhegnet måltes den vertikale hastighed i 5,1 m for perioden til 0,45 m/s. Dette viser, at der umiddelbart i toppen af hegnet er luft, som tvinges op over hegnet. I forhold til den horisontale hastighed (5,33 m/s) udgør den vertikale 8-9 %.

Det formodes, at den største vertikale vindhastighed optræder netop i niveau med toppen af hegnet og umiddelbart foran, hvor sonicen var placeret. Hvis vertikalhastigheden på 0,45 m/s repræsenterer forholdene for et horisontalt plan foran læhegnet, betyder det, at planet kun skal strække sig 2,4 m opstrøms for at forklare den tidligere beregnede vertikale fluks på 1,1 $m^3$/s/m (= 2,4 m * 0,45 m/s). Den vertikale strømning vurderes derfor at foregå relativt tæt ved læhegnet og have en horisontal udstrækning af samme størrelsesorden som højden af hegnet.

### 4.3.4 Samlet vurdering

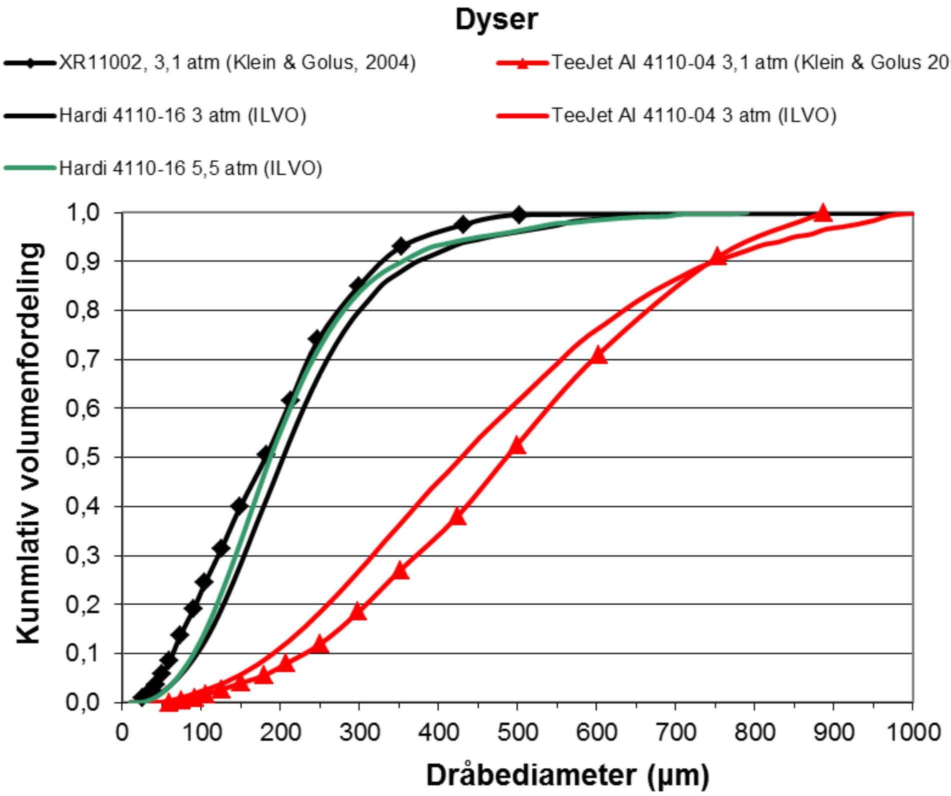
Selv om usikkerhederne på de målte og beregnede horisontale vindhastigheder og flukse er relativt store i forhold til de beregnede forskelle, vurderes det samlet, at 5-10 % af luften passerer op over læhegnet i forhold til den vandrette strømning på marken. Dette gælder dog kun for den type meteorologiske forhold, hvorunder der er målt. Disse forhold dækker dagtimer med let ustabile forhold. Der er ikke målt under stabile forhold som typisk optræder sen aften, nat og tidlig morgen.

Det er den øverste del af luftsøjlen fra marken som løftes over hegnet. Hvis 10 % af luftsøjlen på 5,1 m løftes over hegnet, vil det betyde at den øverste 0,5 m af søjlen passerer over hegnet. Det medfører, at for de nærmeste sprøjtespor ved hegnet, hvor skyen af spray har lille vertikal udbredelse, vil strømningen ikke føre noget af sprayen over hegnet. Først ved sprøjtning i en afstand af ca. 20-25 m fra hegnet har skyen, når den når til hegnet, en vertikal udbredelse, hvor ca. 5 % af skyens masse føres over hegnet. I denne situation vil modelberegninger være lidt konservative.

I hullerne i læhegnet vil der være en øget gennemstrømning af luften (spray) og sammen med, at noget luft løftes over hegnet betyder det, at der reelt vil være mindre spray til rådighed for afsætning end beregnet i spraymodellen, som antager uforstyrret strømning.

## 4.4 Validering af model

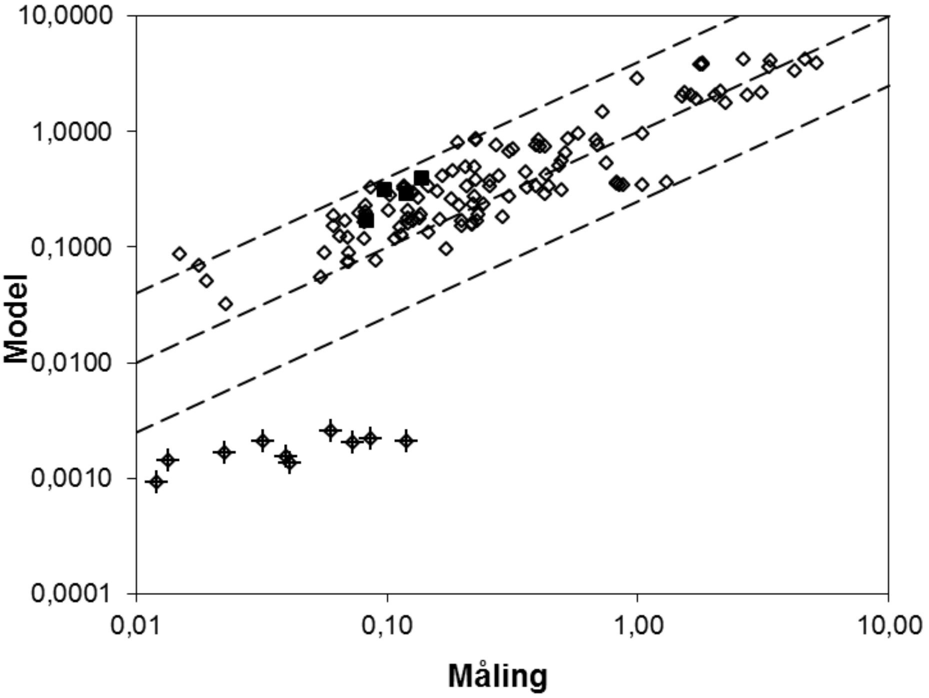
Modellen blev valideret på grundlag af de nye dråbespektre for dyserne. De nye og gamle dråbespektre er sammenlignet i Figur 3.4. Forskellene har ikke haft afgørende betydning for de nye modelberegninger, hvorimod indførelse af ny metode for initiel afdrift har haft større betydning.



**FIGUR 4.4. DEN KUMULEREDE DRÅBESTØRRELSESFORDELING FOR TRE FORSKELLIGE DYSETYPER VED FORSKELLIGT TRYK MÅLT I FORBINDELSE MED DETTE PROJEKT (ILVO) SAMMENLIGNET MED DATA FRA LITTERATUREN (KLEIN & GOLUS 2004), SOM BLEV BENYTTET I DEN FØRSTE UDGAVE AF MODELLEN.**

Modellen er valideret (Figur 3.5) ved at sammenligne beregnet afsætning med uafhængige, målte værdier fra 2010, altså ikke målingerne fra 2005, som er anvendt i forbindelse med opbygning og tilpasning af modellen. I figuren er nogle afvigende punkter markeret med et kryds. Punkterne er for målinger i 4 m umiddelbart op ad sprøjtebommen i 0 m. Der måles betydeligt højere værdier end beregnet, hvilket kan skyldes, at traktoren skaber forøget turbulens, som 'fanger' en lille del af sprayskyen og fører den hurtigt op i højden. Modellen har ikke indarbejdet denne effekt. Sammenligningen for alle punkter giver $R^2$ på 0,78 med 91 % procent af beregningerne liggende inden for en faktor 4 af målingerne. Dette er et godt resultat når det tages i betragtning, at målingerne repræsenterer meget kortvarige eksponeringer, som er udsat for stor stokastisk variation grundet luftens turbulens.

Da modellen er udviklet på basis af data fra fladsprededysen og valideret mod luftinklusionsdysen styrker det troværdigheden til modellen.



FIGUR 4.5. MÅLTE OG MODELBEREGNEDE VÆRDIER FOR HORISONTAL AFDRIFT. DE AFVIGENDE VÆRDIER MARKERET MED KRYDS ER MÅLINGER LIGE VED SIDEN AF SPRØJTEN I 4 M HØJDE, MENS DE SORTE KVADRATER ANGIVER MIDDELVÆRDIER FOR 10 GENTAGELSER I AFSTAND 24 M I 4 HØJDE.

## 4.5 Scenarieberegninger

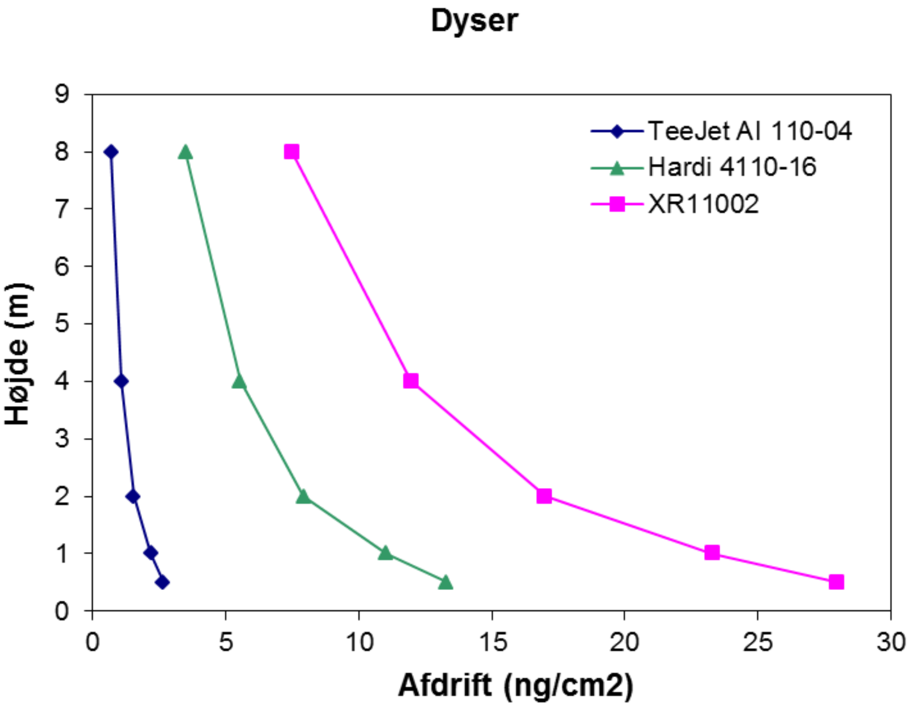
Scenarieberegningerne er opdelt i tre grupper: En gruppe som beskriver betydningen af sprøjteudstyret, en gruppe som beskriver betydningen af de meteorologiske forhold samt en gruppe, som beskriver betydningen af geometrien af marken, dvs. størrelsen af bufferzoner, bredden af marken og vindens retning i forhold til markkanten.

Den horisontale afsætning er her angivet som procent af den nominelle markdosis i forskellige afstande fra markkanten.

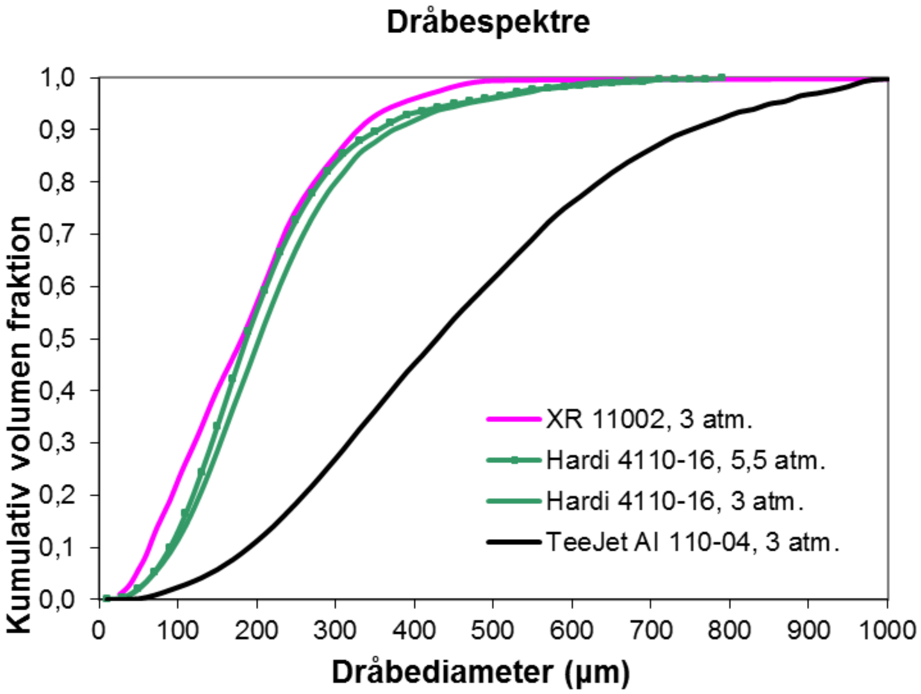
Scenarierne beskriver afdrift og horisontal afsætning fra en sprøjtet mark, som er 240 m bred, og hvor vinden er vinkelret på markkanten. I situationer med bufferzoner langs markkanten er den sprøjtede andel af marken tilsvarende mindre.

### 4.5.1 Betydningen af sprøjteudstyr og –indstillinger

Den videreudviklede model forudser ligesom den tidligere model (Bruus et al. 2008) store forskelle i afdrift af pesticider til læhegn ved brug af forskellige typer af dyser (Figur 3.6): En almindelig luftinjektionsdyse ISO 04 (TeeJet AI 11004), samt fladsprededyserne Hardi 4110-16 og XR11002. Her er det dysernes forskellige dråbespektre (Figur 3.7), som er afgørende for størrelsen af afdriften. XR 11002 har de fleste små dråber, hvorfor afdriften også er størst. Forskellen er størst nederst i hegnet.

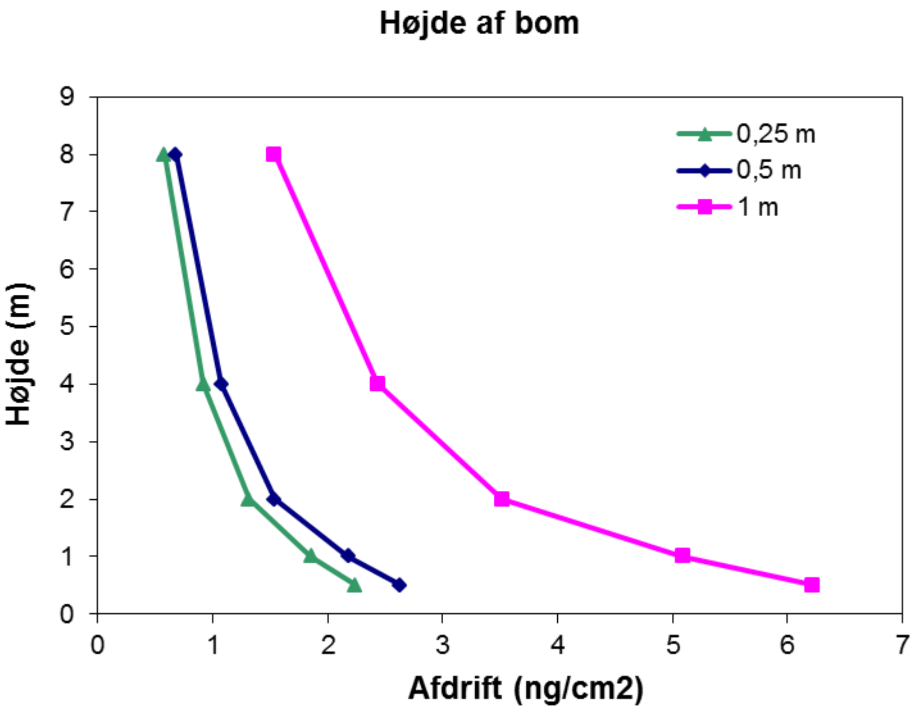


FIGUR 4.6. MODELBEREGNET AFDRIFT VED BRUG AF TRE FORSKELLIGE DYSER. HARDI 4110-16 OG XR11002 REPRÆSENTERER TRADITIONELLE FLADSPREDEDYSER, MENS TEEJETAI110-04 ER EN LUFTINJEKTIONSDYSE. ØVRIGE PARAMETRE FOR MODELKØRSLERNE ER BESKREVET I TEKSTEN.



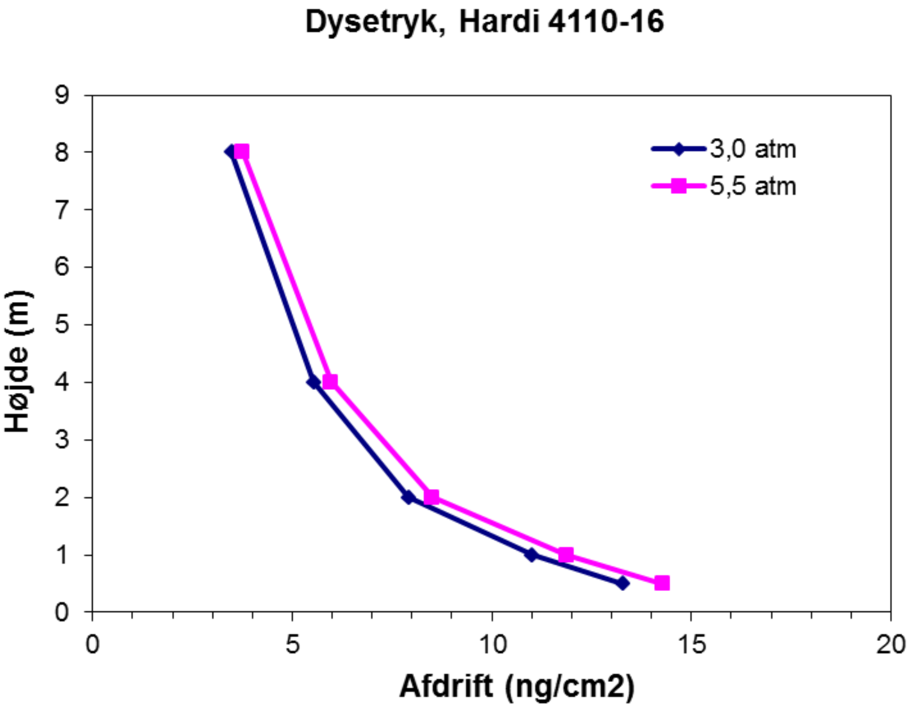
FIGUR 4.7. DRÅBESPEKTRE FOR LUFTINJEKTIONSDYSEN TEEJET AI 110-04 VED 3 ATM. SAMT FLADSPREDEDYSERNE XR 11002 OG HARDI 4110-16 VED 3 OG 5,5 ATM.

Modelberegningerne af effekten af sprøjtebommens højde viser, at afdriften vil stige betragteligt, hvis bomhøjden øges fra de anvendte 0,5 m, mens en sænkning af bommen kun vil have minimal effekt (Figur 3.8). Det skal dog præciseres, at beregningerne af bomhøjdens betydningen er noget usikker, idet der ikke er udført forsøg til validering af beregningerne.



FIGUR 4.8. MODELBEREGNINGER AF EFFEKTEN PÅ AFDRIFTEN TIL LÆHEGN AF AT ÆNDRE SPRØJTEBOMMENS HØJDE OVER AFGRØDEN.

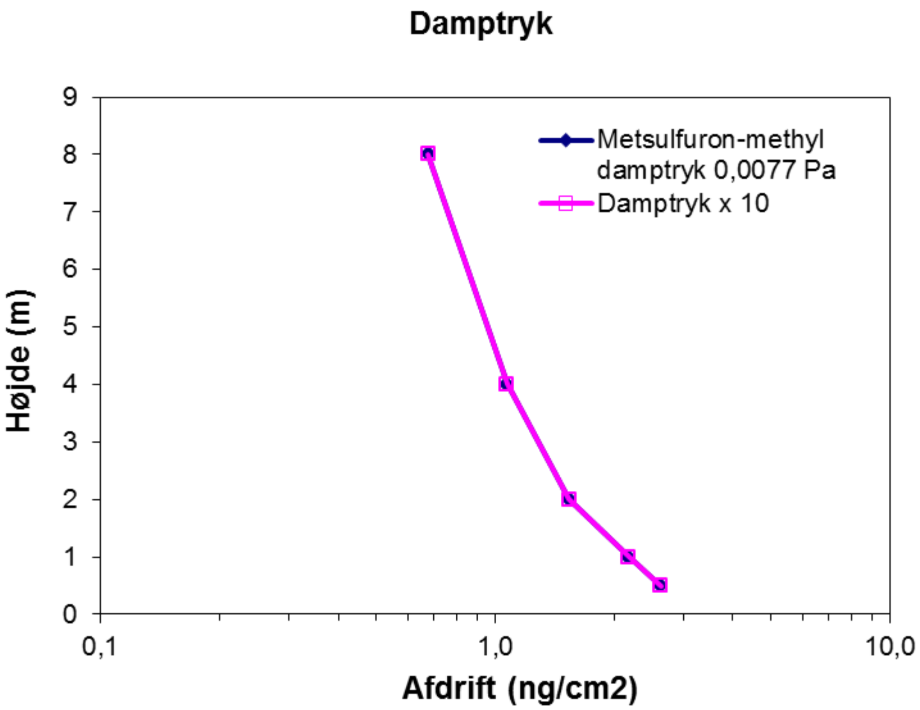
De nye modelberegninger af betydningen af dysetryk er udført for dysen Hardi 4110-16, da vi kun har data til validering for varierende dysetryk for denne dyse. Beregningerne viser (Figur 3.9), at en ændring af trykket på 2,5 atm. kun har begrænset betydning for afdriften, hvilket skyldes, at dråbespektrene for de to tryk er næsten ens. Kurven for 5,5 atm ligger over 3 atm, fordi der ved højere tryk dannes relativt flere små dråber.



FIGUR 4.9. MODELBEREGNINGER AF BETYDNINGEN AF DYSETRYK PÅ AFSÆTNINGEN I LÆHEGN VED SPRØJTNING MED DYSEN HARDI 4110-16.

### 4.5.2 Betydningen af pesticidets damptryk

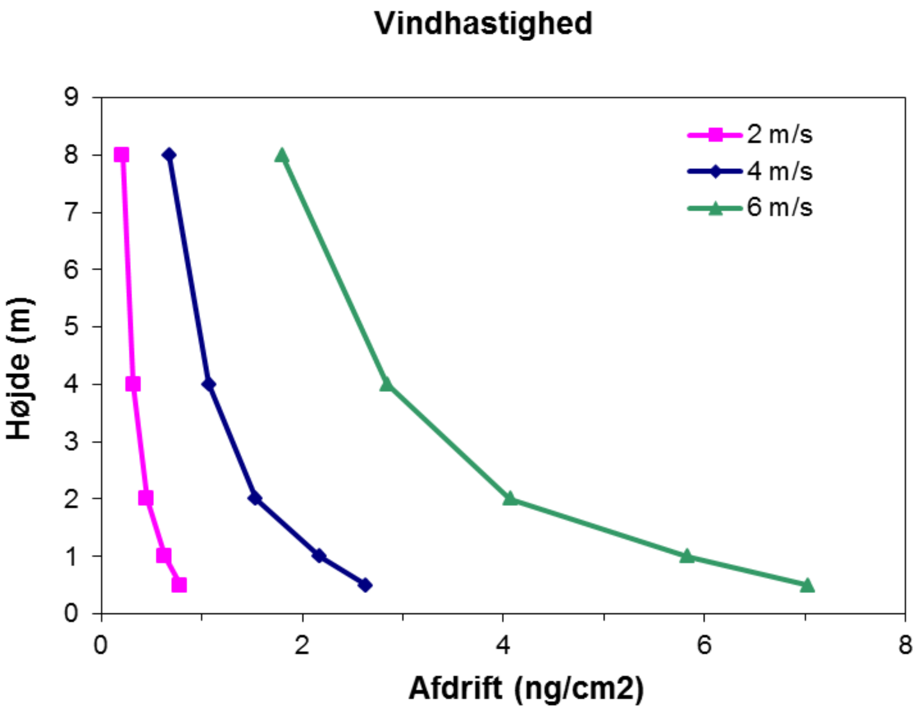
Med den udviklede model er det undersøgt, hvad det anvendte pesticids damptryk har af betydning. Figur 3.10 sammenligner metsulfuron-methyl med et hypotetisk pesticid med 10 gange så højt damptryk. Der er reelt ingen forskel, hvilket skyldes at damptrykket i forvejen er så lavt, at der kun er en meget lille fordampning af pesticidet. Damptrykket for metsulfuron-methyl er ca. 100.000 gange mindre end vanddamps tryk.



FIGUR 4.10. MODELBEREGNINGER AF BETYDNINGEN AF PESTICIDERS DAMPTRYK PÅ AFSÆTNINGEN I LÆHEGN. AFSÆTNINGEN VED SPRØJTNING MED METSULFURON-METHYL ER SAMMENLIGNET MED ET HYPOTETISK PESTICID MED ET 10 GANGE SÅ HØJT DAMPTRYK.

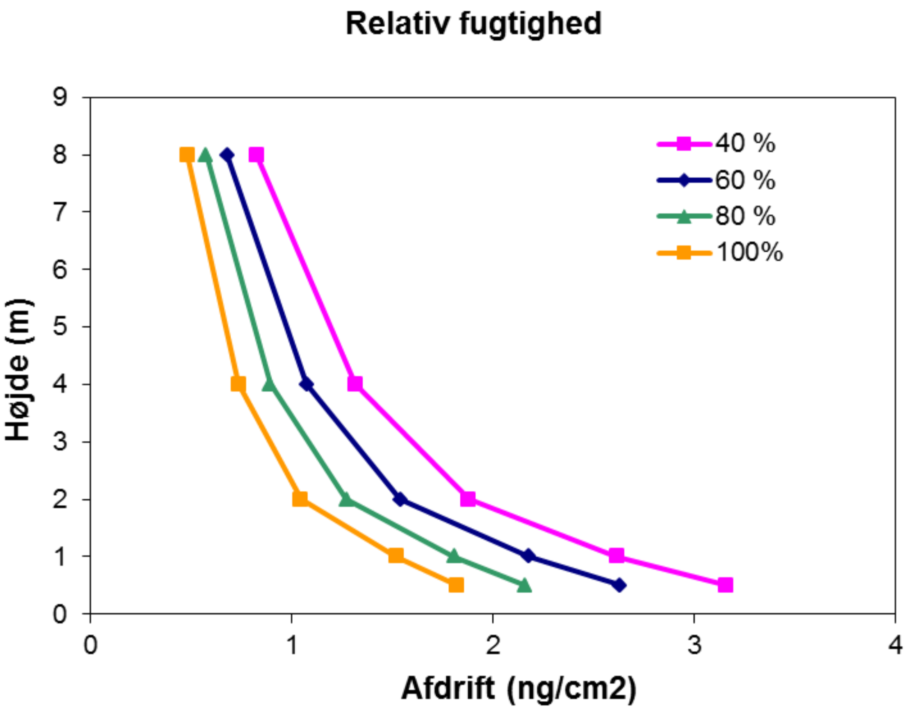
### 4.5.3 Betydning af meteorologiske forhold

Det er velkendt, at vindhastigheden er en afgørende faktor for størrelsen af afdriften. Modelberegningerne viser da også, at vindhastigheden betyder meget for afdriften (Figur 3.11), og at vinden betyder mest nederst i hegnet. Der ses en større relativ effekt af vindhastigheden ift. tidligere beregninger for dyse XR11002 (Bruus et al. 2008). Det skyldes, at afdriften fra de enkelte sprøjtespor (initial afdrift) tidligere antoges stort set at være proportional med vindhastigheden, hvorimod den initielle afdrift i den nye model anvender princippet med ’Tilting Plume’, som tager hensyn til dels dråbernes faldvej indenfor sporet, og dels hvor meget sprayskyen udvider sig inden for sporet, hvor begge processer er tilnærmelsesvis er funktion af vindhastigheden, så der er en større afhængighed af vindhastigheden.



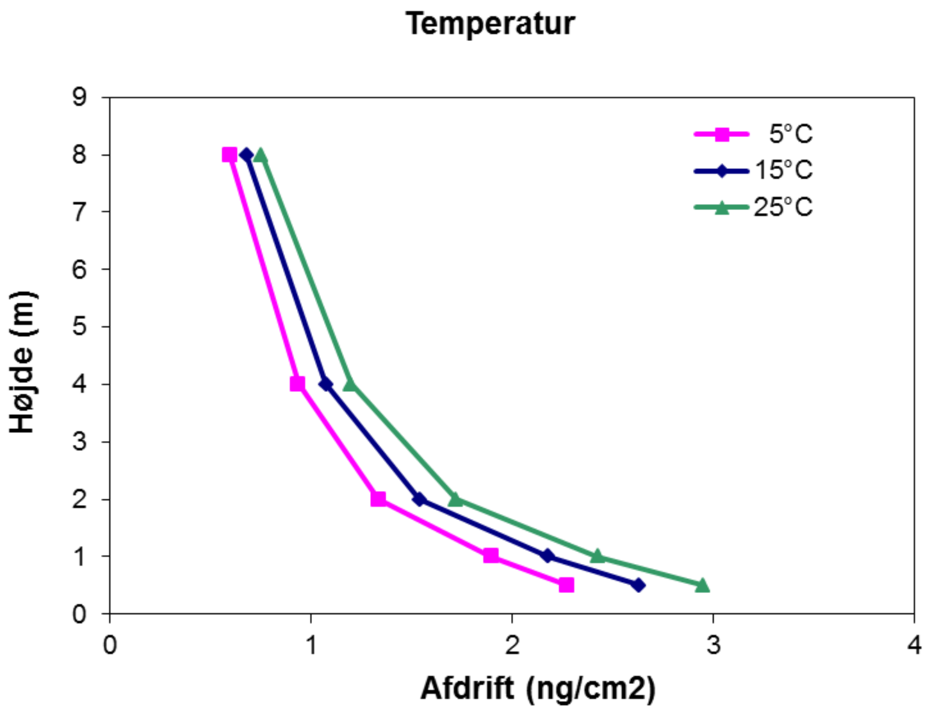
FIGUR 4.11. MODELBEREGNINGER AF EFFEKTEN AF VINDHASTIGHEDEN PÅ AFSÆTNINGEN AF SPRØJTEMIDDEL I LÆHEGN.

Luftens fugtighed har også betydning for afdriften (Figur 3.12). Således mindskes afdriften ved højere relative luftfugtigheder. Ved høj fugtighed fordamper vandet fra dråberne langsommere, og dråberne er større, hvilket medfører større faldhastighed og større afsætning, hvilket mindsker afdriften. Der ses en relativ større indbyrdes forskel mellem kurverne end i de tilsvarende beregninger med den gamle model (Bruus et al. 2008). Det skyldes, at afdriften fra de enkelte sprøjtespor (initiel afdrift) tidligere kun afhang af vindhastigheden, og fugtigheden kun havde indflydelse på afdriften uden for sporet, hvorimod den initielle afdrift i den nye model ('Tilting Plume') også er påvirket af forskelle i dråbernes faldlængde.

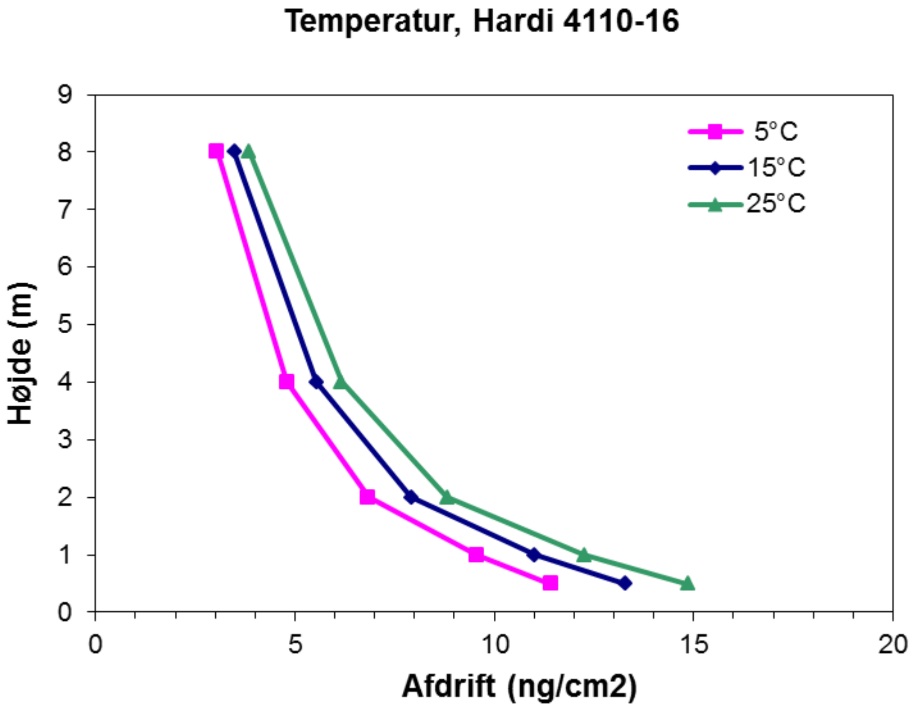


FIGUR 4.12. MODELLERET AFDRIFT FOR FIRE FORSKELLIGE VÆRDIER AF DEN RELATIVE LUFTFUGTIGHED. ØVRIGE PARAMETRE FOR MODELKØRSLERNE ER BESKREVET I TEKSTEN.

Den største afdrift findes ved den højeste temperatur (Figur 3.13). Forklaringen svarer til effekten af mindsket fugtighed: fordampningen øges ved større temperatur. Igen ses en større relativ forskel mellem kurverne end i de tilsvarende beregninger med den gamle model (Bruus el al. 2008) og igen skyldes det, at afdriften fra de enkelte sprøjtespor (initiel afdrift) tidligere kun afhang af vindhastigheden, og temperaturens indflydelse kun havde indflydelse på afdriften uden for sporet, hvorimod den initielle afdrift i den ny model ('Tilting Plume') også er påvirket af dråbernes ændrede faldlængde via temperaturen. Forskellen i forhold til den gamle model er ikke, at der er regnet for to forskellige dyser, hvilket Figur 3.14 viser. Her ses en tilsvarende betydning af temperaturens for afdriften for dysen Hardi 4110-16.



FIGUR 4.13. MODELLERET AFDRIFT FOR TRE FORSKELLIGE LUFTTEMPERATURER VED SPRØJTNING MED DYSEN TEEJET AI 4110-04. ØVRIGE PARAMETRE FOR MODELKØRSLERNE ER BESKREVET I TEKSTEN.



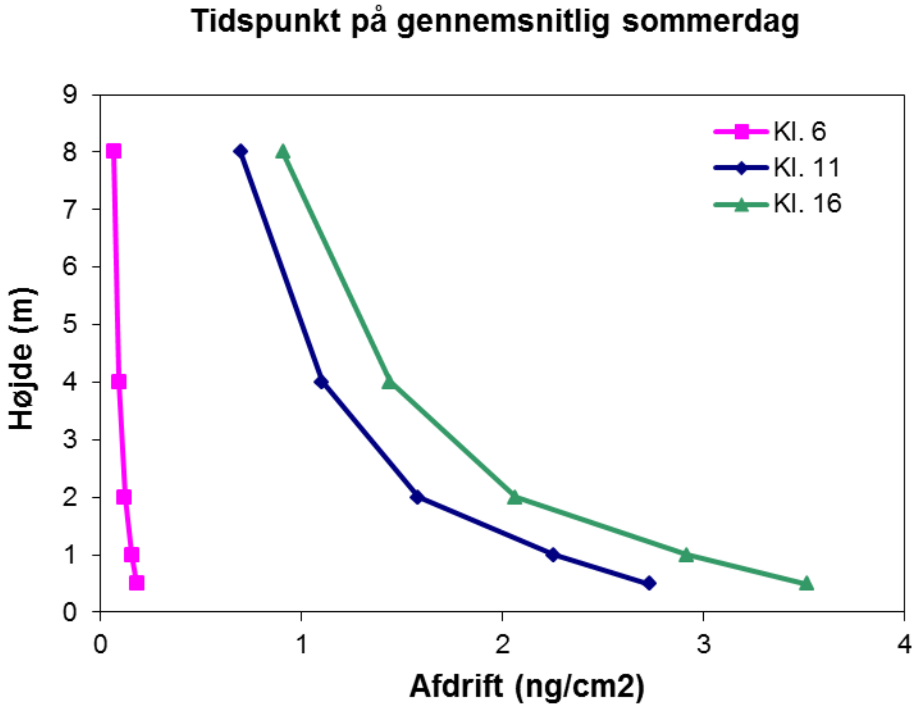
FIGUR 4.14. MODELLERET AFDRIFT FOR TRE FORSKELLIGE LUFTTEMPERATURER FOR DYSEN HARDI 4110-16. ØVRIGE PARAMETRE FOR MODELKØRSLERNE ER BESKREVET I TEKSTEN.

Et eksempel på en samlet effekt af vindhastighed, fugtighed, og temperatur er vist i Figur 3.15 med beregninger for tre forskellige meteorologiske situationer. Situationerne er for tre tidspunkter kl. 6, 11 og 16 på en gennemsnitlig dansk sommerdag beregnet som gennemsnit for de fire sommermåneder maj til august for en mark ved Ringsted i 2005 (Tabel 5.1). Der ses en større relativ forskel mellem kurverne end i de tilsvarende beregninger med den gamle model (Bruus et al. 2008), hvilket skyldes den ovenfor nævnte større følsomhed over for de meteorologiske parametre i den nye model.

TABEL 4.1. METEOROLOGISKE PARAMETRE BRUGT I BEREGNINGERNE FOR TRE KLOKKESLÆT PÅ EN TYPISK SOMMERDAG.

| Klokkeslæt (sommertid) | Vindhast, (m/s) | Relativ fugtighed | Temp. (°C) | $u_*$ (m/s) | Varmefluks (W/m$^2$) | Monin-Obukhov længde* (m) |
|---|---|---|---|---|---|---|
| 6 | 2,9 | 94,7 | 11,5 | 0,207 | -3,4 | 269,1 |
| 11 | 4,6 | 70,1 | 16,7 | 0,415 | 102,2 | -72,1 |
| 16 | 5,0 | 62,0 | 18,2 | 0,442 | 102,4 | -87,0 |

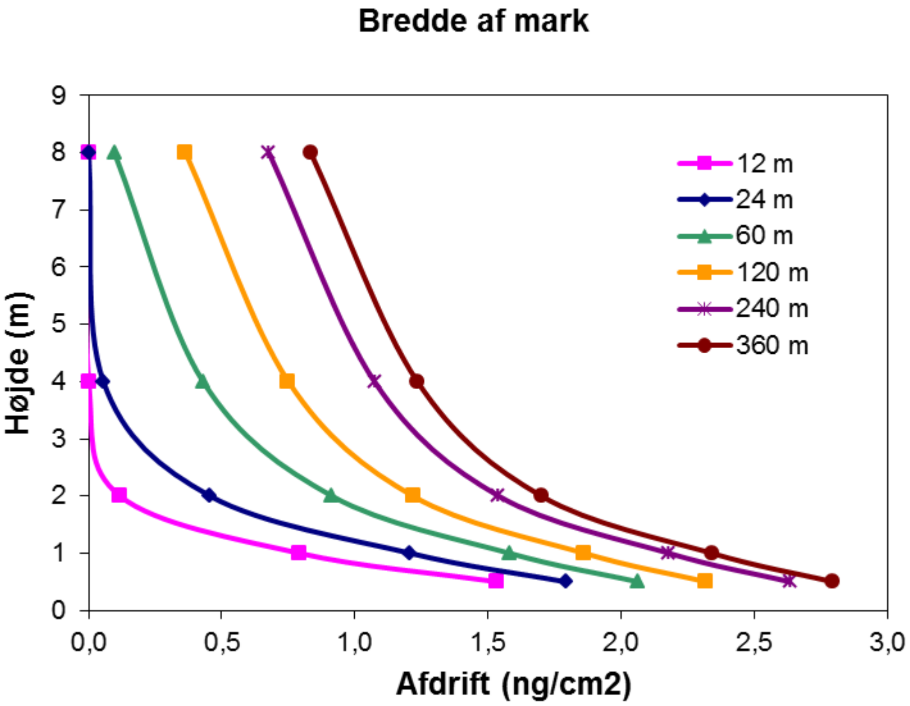
* ET MÅL FOR ATMOSFÆRENS STABILITET



FIGUR 4.15. MODELLERET AFDRIFT FOR TRE FORSKELLIGE TIDSPUNKTER (ANGIVET I FIGUR) OG DERMED TRE FORSKELLIGE METEOROLOGISKE FORHOLD PÅ EN GENNEMSNITLIG SOMMERDAG. METEOROLOGISKE PARAMETRE ER BEREGNET SOM GENNEMSNIT FOR DE 4 MÅNEDER MAJ TIL AUGUST FOR EN MARK VED RINGSTED I 2005. TIDSPUNKTERNE VARIERER MED HENSYN TIL VINDHASTIGHED, ATMOSFÆRISK STABILITET, TEMPERATUR OG FUGTIGHED, SOM ANGIVET I TABEL 4.1. ØVRIGE PARAMETRE FOR MODELKØRSLERNE ER BESKREVET I TEKSTEN.

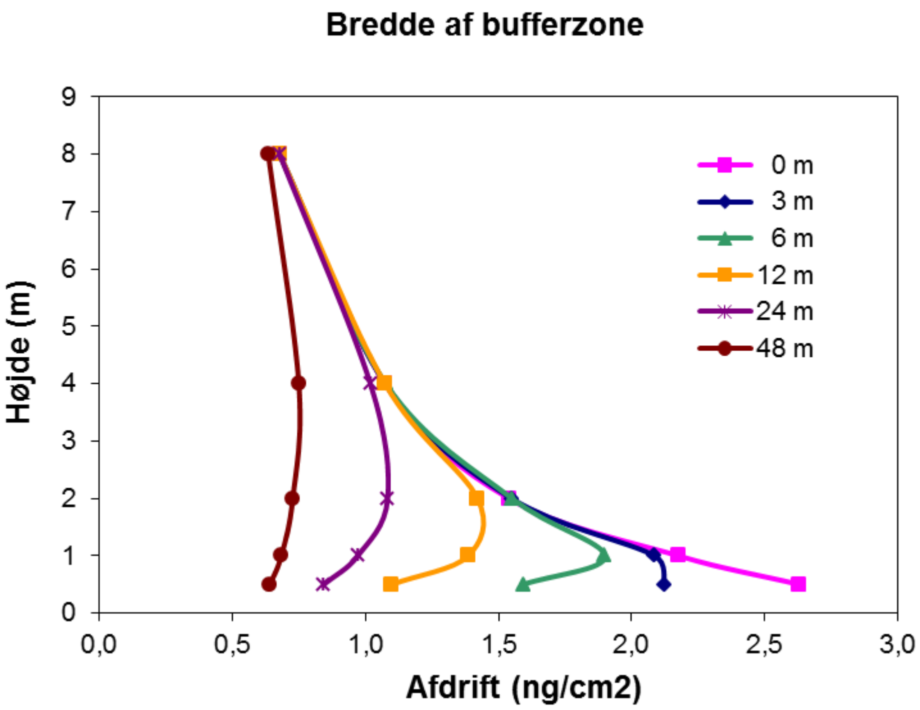
### 4.5.4 Betydning af markbredde og bufferzone

Afdriften fra en mark er selvfølgelig afhængig af, hvor stor eller rettere bred marken er i vindretningen. Det første sprøjtespor nærmest markkanten bidrager relativt mest til afdriften i de nederste meter af et læhegn; men afdrift fra hele marken bidrager dog med aftagende relativ betydning. Specielt i større højde er bidraget til afdriften fra fjernere spor relativ stor (Figur 3.16). Betydningen af de fjernere sprøjtespor viser vigtigheden af at medregne hele det sprøjtede areal.



FIGUR 4.16. MODELBEREGNINGER AF BETYDNINGEN AF BREDDEN (M) AF DEN SPRØJTEDE MARK, DVS. BREDDEN AF DET MEDREGNEDE SPRØJTEDE AREAL. ØVRIGE PARAMETRE FOR MODELKØRSLERNE ER BESKREVET I TEKSTEN.

På grund af forskellen i fjernereliggende sprøjtespors betydning for afdriften til forskellige højder, har virkningen af sprøjtefri bufferzoner ved markkanten også størst reducerende effekt på afdriften i de lave højder af et læhegn. Dette fremgår af Figur 3.17, som viser modelberegninger af effekten af forskellige bredder på bufferzoner. Marken er, som i de øvrige beregninger 240 m bred, hvilket betyder at den totale sprøjtede mængde mindskes proportionalt med bufferzonen, hvilket dog har mindre betydning. Bidraget fra fjernere afstande for en eventuel bredere mark vil være ens for alle zonebredder.

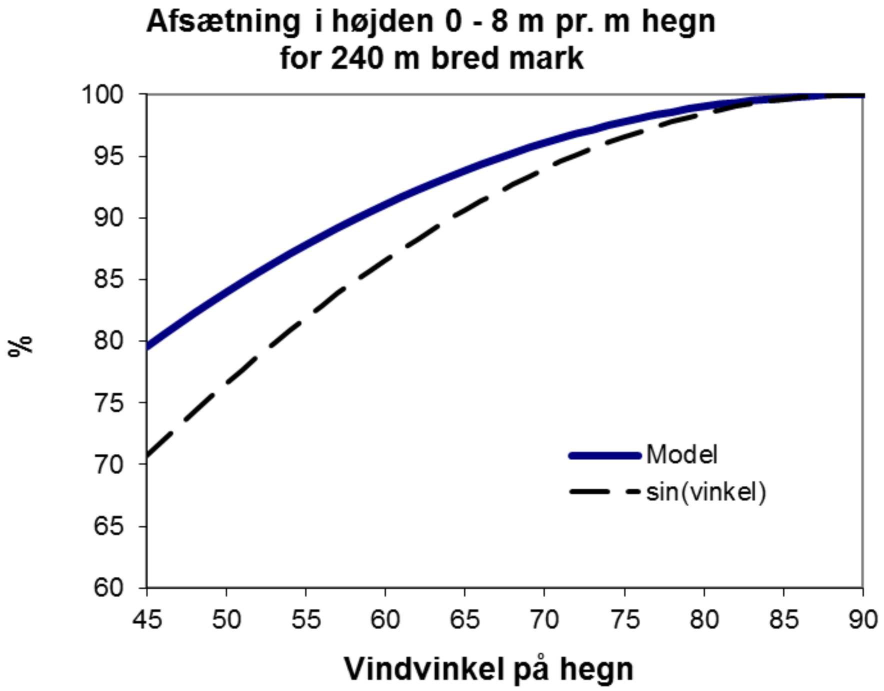


FIGUR 4.17. MODELBEREGNING AF EFFEKTEN AF USPRØJTEDE BUFFERZONER AF FORSKELLIG BREDDE PÅ AFDRIFTEN AF PESTICID TIL LÆHEGN. I BEREGNINGERNE INDGÅR AFDRIFT FRA DE NÆRMESTE 240 M FRA EN MARK. ET EVENTUELT BIDRAG FRA MARKEN I STØRRE AFSTANDE ER ENS FOR ALLE ZONEBREDDER. ØVRIGE PARAMETRE FOR MODELKØRSLERNE ER BESKREVET I TEKSTEN.

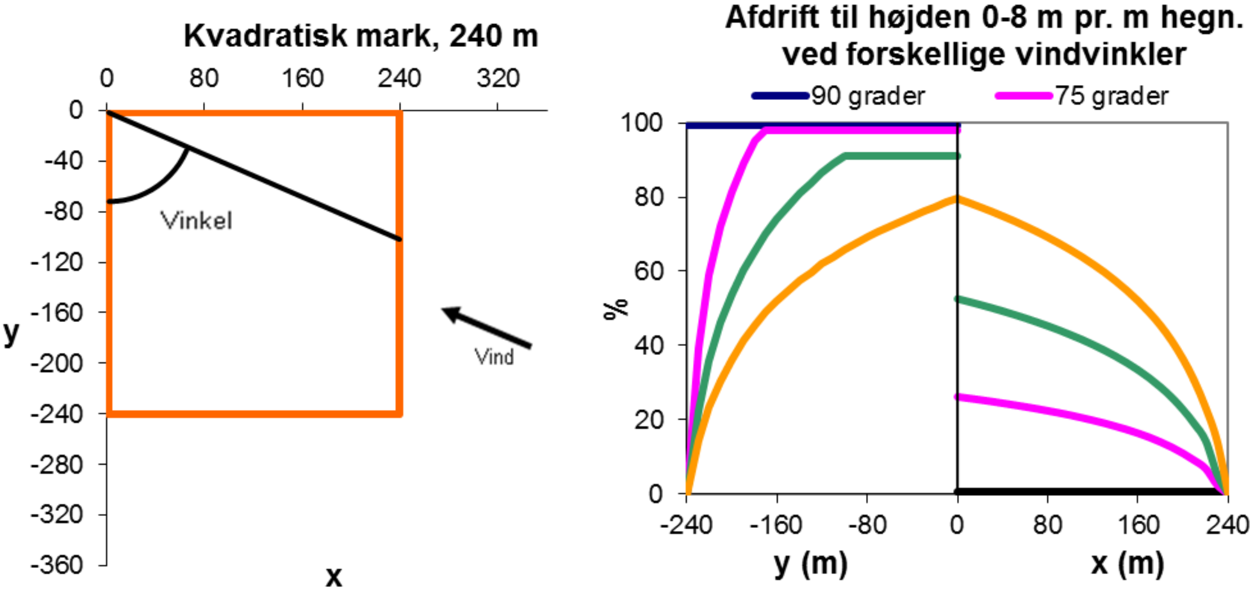
### 4.5.5 Betydningen af vindens vinkel på hegn

Når vindretningen ikke er vinkelret på marktanten eller læhegnet, vil afdriften ændres. For en given markbredde, målt vinkelret på markkanten, vil vindens strækning over marken øges, når retningen ikke er vinkelret på kanten. Derved kan der opsamles mere spray frem til kanten eller læhegnet, når man måler pr. meter vinkelret på vinden, men da den opsamlede spray skal afsættes i et læhegn, som står på skrå i forhold til vinden, vil afsætningen ske på en længde af hegnet, som er større. Sinus til indfaldsvinklen bliver større, og dermed modvirkes effekten fra opsamlingen fra det længere bestrøgne markstykke noget. Præcist hvor meget de to effekter betyder, kan ses af beregningerne i Figur 3.18.

For en kvadratisk mark er situationen mere kompliceret, idet marken har en endelig udstrækning, og den bestrøgne opvindslængde varierer noget anderledes. I Figur 3.19 er vist beregninger af den relative variation i afdriften til to af siderne i en kvadratisk mark for forskellige vindretninger. Da modellen ikke tager hensyn til den horisontale spredning, hvilket ikke har betydning midt på læhegnet, vil kurveforløbene reelt være en smule mere udglattede. Den samlede afdrift til hele hegnet svarer til arealet under kurverne og er i forhold til afdriften for 90 grader 108, 112 og 113 % for vindretning på 75, 60 respektive 45 grader. De indbyrdes forskelle skyldes, at sprøjtning af de nærmeste meter ved hegnet er relativt mere betydende end de fjernere meter, og ved øget vinkel øges antallet af ’nærmeste’ meter.



FIGUR 4.18. MODELLERET SAMLET AFDRIFT I 0 TIL 8 M OVER JORDEN SOM FUNKTION AF VINDENS VINKEL PÅ MARKKANT (LÆHEGN). AFDRIFTEN ER VIST SOM PROCENT AF AFSÆTNINGEN I FORHOLD TIL VIND VINKELRET PÅ MARKKANTEN OG BEREGNET PR. LØBENDE METER. MARKEN ER ANTAGET MEGET LÆNGERE END BREDDEN PÅ 240 M, HVILKET BETYDER, AT VED VINKLER MINDRE END 90 MODTAGER KANTEN/LÆHEGNET AFDRIFT FRA EN LÆNGERE STRÆKNING AF MARKEN; MEN MÆNGDEN PROJICERES UD PÅ ET LÆNGERE STYKKE AF LÆHEGNET. KURVEN 'SINUS' REPRÆSENTERER ALENE EN KORREKTION FOR PROJEKTIONEN. ØVRIGE PARAMETRE FOR MODELKØRSLERNE ER BESKREVET I TEKSTEN.

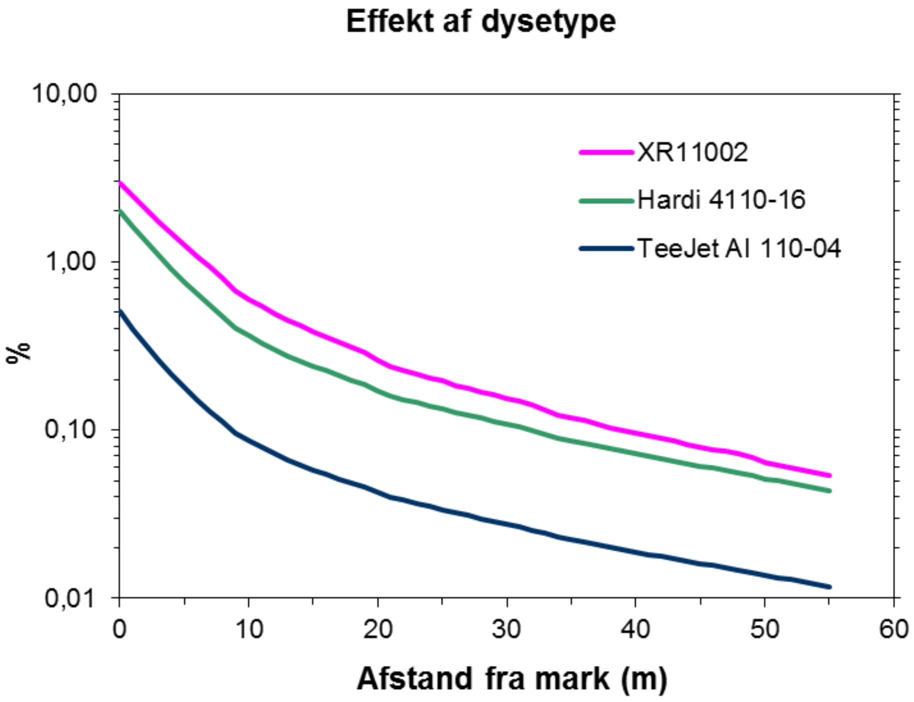


FIGUR 4.19. SKITSE AF KVADRATISK MARK (T.V.) ANVENDT I MODELLERING AF AFDRIFT (T.H.) TIL LÆHEGN OMKRING MARKEN FOR UDVALGTE VINDVINKLER MELLEM 90° OG 45°. DA MODELLEN IKKE INDDRAGER DEN HORISONTALE SPREDNING, HVILKET IKKE HAR BETYDNING MIDT PÅ LÆHEGNET, VIL KURVEFORLØBENE REELT VÆRE LIDT MERE UDGLATTEDE OMKRING MARKHJØRNERNE, SPECIELT FOR Y = -240 OG 0 M SAMT FOR X = 240 M. ØVRIGE PARAMETRE FOR MODELKØRSLERNE ER BESKREVET I TEKSTEN.

### 4.5.6 Horisontal afsætning

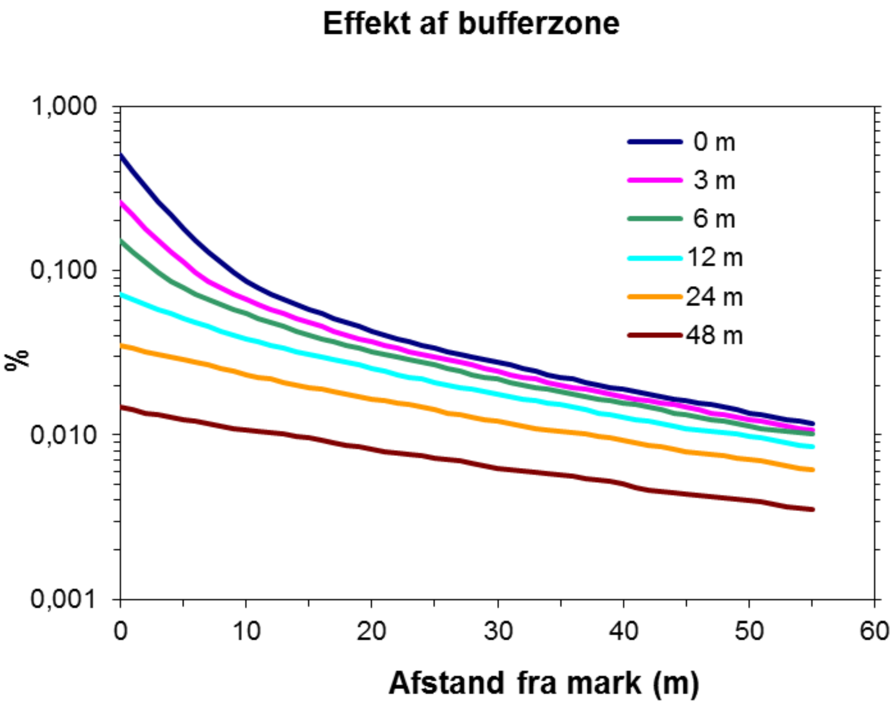
Den horisontale afsætning af pesticid til jordoverfladen uden for mark er belyst i det følgende for nogle vigtige parametre.

Modelberegningerne af den horisontale afsætning uden for marken i forskellige afstande fra markkant ved sprøjtning med forskellige typer dyser viser samme mønster som for den vertikale afsætning (Figur 3.20), idet andelen af små dråber er bestemmende for størrelsen af afdriften. Figuren viser endvidere, at der vil afsættes mellem 0,5 og 3 % af den udsprøjtede dosering. Bemærk, at skalaen for afsætning er logaritmisk.



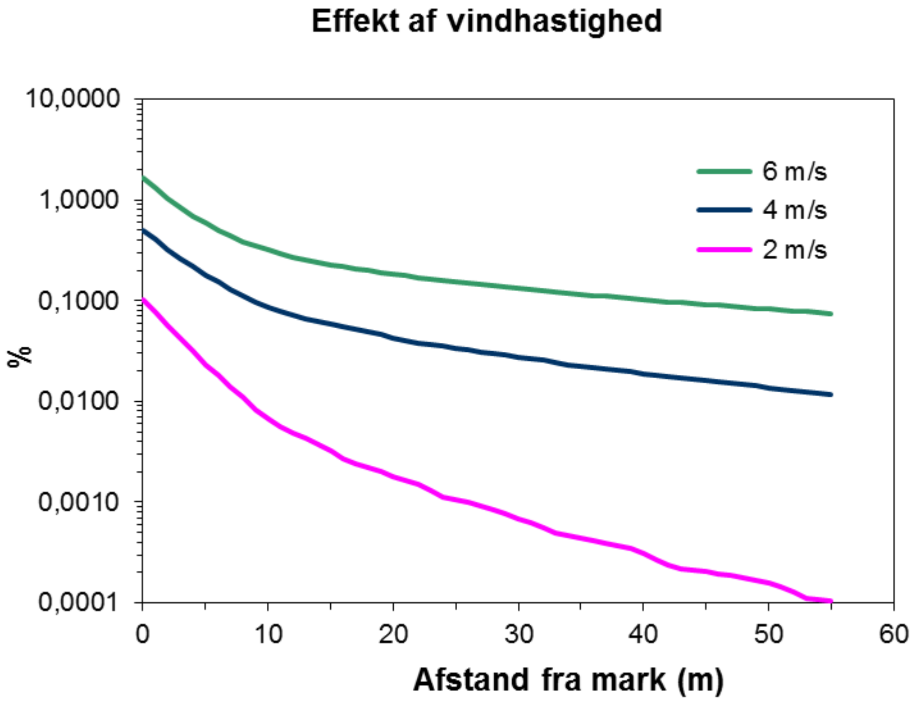
FIGUR 4.20. HORISONTAL AFSÆTNING UDEN FOR EN 240 M BRED MARK I FORSKELLIGE AFSTANDE FRA MARKKANT VED FORSKELLIGE DYSER. Y-AKSE ANGIVER DEN PROCENTVISE AFSÆTNING I FORHOLD TIL NOMINEL MARKDOSIS PÅ 4 G/HA. ØVRIGE MODELPARAMETRE ER BESKREVET I TEKSTEN.

Tilsvarende beregninger for effekten af sprøjtefrie bufferzoner på afdrift af pesticider til arealer lige uden for marken viser en tydelig effekt af bufferzonerne, især tæt på marken (Figur 3.21). Marken er som i de øvrige 'standard'- beregninger 240 m bred, hvilket betyder at den totale sprøjtede mængde mindskes proportionalt med bufferzonen; men forskellen i afdrift skyldes næsten udelukkende, at afstanden til nærmaste sprøjtesporet øges. Bidraget fra fjernere afstande for en eventuel bredere mark vil være ens for alle zonebredder.



FIGUR 4.21. HORISONTAL AFSÆTNING UDEN FOR MARKEN I FORSKELLIGE AFSTANDE FRA MARKKANT VED FORSKELLIGE BREDDER AF SPRØJTEFRI BUFFERZONE. Y-AKSEN ANGIVER DEN PROCENTVISE AFSÆTNING I FORHOLD TIL NOMINEL MARKDOSIS PÅ 4 G/HA. ØVRIGE MODELPARAMETRE ER BESKREVET I TEKSTEN.

Modellen forudsiger lige som for afdriften til læhegn en kraftig effekt af vindhastigheden på den horisontale afsætning (Figur 3.22). Betydningen af vindhastigheden stiger med afstanden fra marken.



FIGUR 4.22. HORISONTAL AFSÆTNING UDEN FOR MARK I FORSKELLIGE AFSTANDE FRA MARKKANT VED FORSKELLIGE VINDHASTIGHEDER. Y-AKSE ANGIVER DEN PROCENTVISE AFSÆTNING I FORHOLD TIL NOMINEL MARKDOSIS PÅ 4 G/HA. ØVRIGE MODELPARAMETRE ER BESKREVET I TEKSTEN.

# 5. Diskussion

Den seneste tilpasning af modellen har ikke ændret på de overordnede forudsigelser mht. effekter af sprøjteudstyr og –indstillinger, meteorologiske forhold og bufferzoner, men de nye data for dråbestørrelsesfordelingerne samt den ny metode til beregning af initiel afdrift har øget pålideligheden af modellen, idet den initielle afdrift er beregnet under hensyntagen til flere relevante fysiske forhold. Valideringen af modellen viser dog, at modellens evne til at forudsige afsætning i toppen af hegnet, når traktoren kører helt tæt på hegnet, ikke er særligt god. Afvigelserne mellem model og målinger skyldes formentlig, at traktoren, ligesom en høj bygning, genererer en ekstra turbulens, som hvirvler dråberne højt op, hvilket modellen ikke tager højde for.

Modellen har en række fordele sammenlignet med andre typer af modeller beskrevet i litteraturen. Den nye model beregner afdriften på få sekunder og vil med en brugervenlig menu kunne anvendes af de fleste inden for sprayfagområdet. Som alternativ har de såkaldte CFD-modeller (Computational fluid dynamic models) den fordel, at de kan beregne meget komplicerede strømninger og spredning lige omkring sprøjtebom og dyser; men er ekstremt ressourcekrævende med hensyn til regnetid samt eksperttid til opsætning og tuning af model til hver ny konfiguration af sprøjteudstyr. De kan reelt kun beregne afsætning i den umiddelbare nærhed af et sprøjtespor og vil i praksis ikke kunne tage hensyn til fjerne sprøjtespor. CFD-modeller er således ikke anvendelige til hurtigt, administrativt brug. De såkaldte trajektorie-modeller, som følger tusindvis at udsendte dråber og beregner 'hit'-statistik i en given afstand, er også meget computerintensive, specielt ved større afstande, hvor der kræves flest dråbeudslip for en tilstrækkelig sikker statistik. Beregningstiden er reelt for stor til administrativt brug. Såvel CFD- som trajektorie-modeller er kun udviklet til neutrale atmosfæriske forhold og kan således ikke beregne for stabile forhold, som typisk optræder i de tidlige morgentimer eller sene aftentimer. De såkaldte TiltingPlume-modeller, som bygger på Gaussiske røgfane-modeller, hvor centerlinjen synker med samme hastighed som dråberne falder, foretager beregninger meget hurtigt, men modeltypen undervurderer den horisontale afsætning, når afstanden bliver mere end cirka 20-30 m, og dermed bliver bidrag for fjernere sprøjtespor undervurderet.

Sammenligner man afdriften til læhegn ved anvendelse af luftinjektionsdysen TeeJet AI 4110-04 (dette projekt) med de tidligere målinger ved anvendelse af fladsprededysen Hardi 4110-16, er det svært ud fra målingerne i felten helt at skelne effekten af dysetypen fra effekten af især de meteorologiske betingelser, som varierede en del imellem de forskellige sprøjtninger. Modelberegningerne viser imidlertid klart, at den afdriftsreducerende dyse har den forventede effekt (en reduktion af afdriften på ca. 75 % ved det anvendte tryk iflg. BBA (2007)) både på afdriften til læhegn og på den vandrette afsætning. Dette er også demonstreret i artiklen "Pesticide deposition due to spray drift into hedgerows from multiple spray swaths" (Kapitel 3), idet de forudsete værdier for TeeJet AI 4110-04 ud fra variansanalysen af afdriftsdata for Hardi 4110-16 ligger betydeligt over de målte værdier.

Den direkte måling af den vandrette afsætning målt på filterpapirer er betydeligt mindre end den indirekte målt på curlere. Det kan skyldes, dels at filterpapirerne står lidt i 'skygge' af afgrøden, hvorved der opsamles mindre, og dels at afgrøden er mere effektiv til at 'filtrerer' sprøjteskyen end et flad papiroverflade. Den indirekte måling er sandsynligvis den mest korrekte.

Modellen deponerer tilsyneladende for lidt i forhold til den indirekte måling. Modellens undervurdering af depositionen skyldes formodentligt, at modellen kun via den aerodynamiske ruhed kan skelne mellem flad mark og høj vegetation, men ikke at vegetationen stikker delvist op i vinden, 'filtrerer' luften og øger depositionen, som det er tilfældet i 2010. Den høje vegetation optræder også 9. juni 2005 i Bruus et al. (2008). For de nævnte dage er der en tendens til, at modellen overvurderer mastemålingerne i større afstande, hvilket igen indikerer for lav deposition. For de øvrige dage i 2005 med lav vegetation udviser modellen ikke samme overvurdering med afstanden.

Mht. betydningen af diverse faktorer for afdriften til læhegn viser modelberegningerne samt analyserne af data i Kapitel 3, at vindhastigheden er den vigtigste meteorologiske parameter i forhold til størrelsen af afdriften, hvilket er i overensstemmelse med, hvad bl.a. Arvidsson et al. (2009) fandt i deres afdriftsforsøg.

Modellens beregninger af betydningen af sprøjtebommens højde over afgrøden understøttes af Arvidsson et al. (2009), som fandt, at afdriften øges med ca. 0,94 procentpoint for hver 10 cm, bommen hæves. Også Nordby & Skuterud (1975) og Nuyttens et al. (2007a) har vist betydningen af bomhøjden.

Det kan synes overraskende, at modellen kun forudsiger en lille effekt af dysetrykket på afdriften, idet dysetrykket generelt betragtes som betydende for afdriftens størrelse (se fx review af Felsot et al. 2011). For den undersøgte fladsprededyse hænger den ringe betydning af dysetrykket dog tæt sammen med, at der kun er en lille øgning i andelen af små dråber (< 100 µm) ved en stigning i dysetrykket fra 3 til 5,5 atm, hvilket ifølge Arvidsson et al. (2011) er bestemmende for afdriftens størrelse fra forskelligt sprøjteudstyr. Desuden viste vore analyser af afsætningen af sprøjtemiddel i læhegn tilsvarende, at dysetrykket var den mindst betydende af de analyserede variable (Bilag 1).

Idet de fleste pesticider har et lavt damptryk (mindre end vand), viser modelberegningerne, at forskelle i damptryk ikke vil have nogen betydning for afdriften. Vi har ikke i litteraturen fundet undersøgelser, der kan understøtte dette resultat.

Tilsammen viser resultaterne og scenarierne i dette projekt og projektet "Vurdering af omfang og effekt af afdrift af ukrudtsmidler til danske læhegn eksemplificeret ved metsulfuron" (Bruus et al. 2008), at der er mange faktorer, som påvirker mængden af pesticid, der driver ud af marken under sprøjtning. Dermed er der også mange måder for landmanden at reducere afdriften. Tilpasningen af modellen har ikke ændret grundlæggende ved, at der er forskel på, hvilke tiltag der vil reducere afdriften til hhv. toppen af et læhegn og til vandrette flader lige uden for marken. Sprøjteudstyret og de meteorologiske forhold påvirker afdriften til begge typer marknær halvnatur, hvorimod bufferzoner har langt større effekt på afdriften til lave, vandrette flader, fx en nabomark eller et vandløb, end på afdriften til strukturer med en vertikal udstrækning som fx læhegn.

Ud over de faktorer, som modellen tager hensyn til, har også andre forhold betydning for, hvor meget pesticid der driver ud af marken. Vi har i de gennemførte forsøg ikke taget hensyn til hegnenes gennemtrængelighed. Andre studier viser, at hegnets gennemtrængelighed har nogen betydning for afsætningen i hegnet. Lazzaro et al. (2008) fandt således, at i hegn med en optisk porøsitet på 0,75 afsættes ca. 83 % af den udsprøjtede mængde ved sprøjtning lige ved siden af hegnet, mens hegn med en porøsitet på 0,11 opfangede 97 %. Raupach et al. (2001) viste, at for dråber større end 30 µm fanger hegn mest ved en optisk porøsitet på 0,2.

Også afgrødens højde og fysiske struktur (fx ruhed) forventes at have betydning for afdriften. Arvidsson et al. (2009) viste således, at afdriften fra en kortklippet græsmark var betydeligt større end afdriften fra en kornmark med en veletableret afgrøde.

# 6. Konklusioner

## 6.1 Status for model

Modellen er nu videreudviklet, så den tager hensyn til, at dråber af forskellig størrelse har forskellig initiel afdrift. Desuden er modellen valideret vha. uafhængige data. I forhold til de målte data er modellen forudsigelsesevne meget god, med undtagelse af afdrift til toppen af læhegnet ved sprøjtning lige ved siden af dette.

Afdriftsmodellen er hermed udviklet til at kunne forudsige afdriften ved brug af de fleste typer af sprøjtemidler og forskellige typer hydrauliske dyser under forskellige meteorologiske forhold, ved forskellige indstillinger af sprøjteudstyret og for pesticider med forskelligt damptryk.

## 6.2 Dysetype og -tryk

Forskellen i afdrift til læhegn og vandrette flader mellem de to typer af dyser viser, at der er et stort potentiale for via valg af sprøjteudstyr at reducere afdriften ved at vælge dysetypen med omhu. Dysens tryk har en meget mindre betydning for afdriften

## 6.3 Pesticidets damptryk

Beregningerne af betydningen af pesticidernes damptryk for afdriftens størrelse viser, at for langt de fleste pesticider vil damptrykket ingen indflydelse have, idet en 10-dobling af damptrykket i forhold til metsulfuron-methyl ingen effekt har på afdriften.

## 6.4 Bomhøjde

Modelberegningerne af sprøjtebommens højde over afgrøden tyder på, at afdriften bliver betydeligt højere, hvis bomhøjden øges, hvorimod en sænkning af bommen i forhold til den anvendte bomhøjde på 0,5 m kun vil have en meget begrænset effekt. Disse beregninger er dog ikke valideret.

## 6.5 Meteorologiske forhold

Feltdata såvel som modelberegninger viser, at vindhastigheden har stor betydning for afdriften til såvel læhegn som vandrette arealer. Betydningen af vindhastigheden er større end betydningen af luftfugtighed og temperatur.

## 6.6 Sprøjtefrie bufferzoner

Modelberegningerne viser, at en sprøjtefri bufferzone yderst i marken vil reducere afdriften til vandrette flader uden for marken betragteligt, og effekten vil være større, jo bredere bufferzonen er. Derimod vil en bufferzone kun have meget lille effekt på afdriften til læhegn, specielt den øverste del af læhegnet, hvor de fleste blomster og bær ofte findes.

# 7. Perspektivering

## 7.1 Forskningsmæssige perspektiver

Selv om modellen nu er stort set færdigudviklet, er der stadig nogle forhold, som den ikke tager hensyn til, og som dermed kunne adresseres i nye projekter. Således inkluderer modellen endnu ikke luftassisterede sprøjter, der adskiller sig ved at blæse dråberne initieret af fartvinden ned i afgrøden igen, før de ender i sprøjteskyen, hvilket ikke umiddelbart kan simuleres vha. den foreliggende model.

Betydningen af kørehastigheden indgår ikke i modellen, idet alle målinger anvendt til udvikling og validering af modellen er baseret på forsøg med kørehastighed på ca. 7 km/t. Ved større hastigheder er det muligt, at traktoren i sig selv vil skabe øget turbulens, som kan påvirke den initielle afdrift.

Idet de forsøg, der ligger til grund for modellen, alle er udført i en kornmark med en afgrødehøjde mellem 0 og 20 cm, vil modellering af afdrift fra sprøjtning af andre typer afgrøder og meget høje afgrøder kræve nye målinger og validering af, at modellens håndtering af forventet større afsætning i marken styret af den øgede aerodynamiske ruhed er korrekt, eller eventuelt kræve yderligere udvikling af modellen.

I den nuværende udgave af modellen tages ikke hensyn til den effekt, selve traktoren har på afdriften pga. den turbulens, der skabes omkring traktoren.

Ligeledes ville det styrke modellen, hvis den blev valideret og evt. tilpasset i forhold til andre typer af hegn. Her tænkes ikke nødvendigvis på andre træarter, men i højere grad på fx meget tætte hegn og evt. meget høje hegn.

Vi ved ikke, hvor meget formuleringen af pesticiderne betyder for afsætningen. Undersøgelser af effekten af formuleringen af pesticider på afdriften viser, at tilsætningsstofferne generelt påvirker dråbestørrelsesfordelingen og dermed den potentielle afdrift (Miller & Butler Ellis 2000). Således fandt Chapple et al. (1993), at ti ud af tolv formuleringer ændrede dråbestørrelsesfordelingen og dermed potentielt afdriften, men at der ikke var nogen klar tendens, idet effekten dels afhang af additivet, dels af hvilken størrelse dråber, man kiggede på. Butler Ellis et al. (1997) undersøgte seks additiver, som alle ændrede dråbestørrelsesfordelingen, men ikke på samme måde. Betydningen af formulering og additiver for dråbestørrelsesfordelingen er således ikke tilstrækkeligt klarlagt, og de enkelte additiver må vurderes hver for sig. Specielt vil det være relevant at undersøge betydningen af emulgerende additiver.

Idet modellen giver et eksponeringsestimat, er det oplagt at tænke det sammen med effekten af de anvendte pesticider på fx hegnsfloraen og dyrene i agerlandet. For hegnenes træer og buske har vi tal på de forekommende arter (Bruus et al. 2008), men mangler estimater af følsomhed af en række arter og pesticider. Tilsvarende gælder for andre typer organismer, hvorfor yderligere undersøgelser af pesticideffekter på relevante organismer vil være ønskelige.

## 7.2 Administrative perspektiver

Med den videreudviklede afdriftsmodel har vi nu et værktøj, som kan anvendes til beregning af afdriften af forskellige typer sprøjtemidler til både læhegn og vandrette flader ved anvendelse af diverse typer hydrauliske dyser og ved varierende indstillinger af sprøjteudstyret. Modellen er desuden optimeret, så den i endnu højere grad end tidligere kan forudsige effekten af afdriftsreducerende tiltag såsom sprøjtefrie bufferzoner og optimale sprøjtebetingelser. Dermed er der nu, om det ønskes, i højere grad end tidligere mulighed for at supplere reguleringen af pesticidanvendelsen med nye måder at nedsætte pesticidbelastningen som alternativer til den hidtil foretrukne metode via regulering af behandlingsindekset. I forbindelse med kravene om en bestemt afstand til fx vandløb ved sprøjtning vil modellen kunne inddrages, så man kan nuancere afstandskravene i forhold til det anvendte sprøjteudstyr, sådan som det også er tilfældet i en del andre lande. I Tyskland vil den krævede afstand til fx vandløb således afhænge af den anvendte dysetype, det anvendte sprøjtetryk samt hvilket middel, der sprøjtes med.

Desuden kan modellen danne baggrund for en mere realistisk risikovurdering, også på EU-niveau, idet den bidrager med mere realistiske estimater af eksponeringen af især habitater med en vertikal udstrækning som fx læhegn. Ligeledes vil det forbedrede eksponeringsestimat for sådanne habitater kunne indgå i EU's godkendelsesordning for pesticider. Ønskes der et udtryk for pesticideffekterne i fx læhegn, skal modellens forudsigelser sammenholdes med data for de tilstedeværende arters følsomhed og forekomst/adfærd. For nuværende findes sådanne data som nævnt kun for få af de relevante arter og for et begrænset udvalg af pesticider.

Skulle man ønske at anvende modellen administrativt, vil det imidlertid kræve, at der udvikles en brugerflade, som modellen tilpasses. For nuværende kan modellen kun anvendes af en modelleringsekspert.

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## Bilag 1: Pesticide deposition in hedgerows due to spray drift from multiple spray swaths

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**Original Article**

# Pesticide drift deposition in hedgerows from multiple spray swaths

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A series of spray experiments was conducted in order to determine deposition at different heights of the hedgerow and to estimate the effect of unsprayed buffer zones on spray deposition. Deposition varied highly with distance, absolute humidity, height, droplet size distribution and wind speed. Eighty-two percent of the observed variation could be accounted for by these factors. Droplet size distribution depended on nozzle type and working pressure, which confirms the potential of these factors for reducing spray drift. Unsprayed buffer zones reduced deposition in hedgerows, but the effect was more pronounced in the lower parts, where a reduction of 72% was obtained by introducing a 12 m buffer zone, whereas at 4 m height the reduction was less than 1%. Therefore, deposition at different heights of the hedgerow should be included in order to make risk assessments relevant for organisms exploiting different parts of the hedgerow.

*Keywords:* hedgerow exposure, spray distribution, environmental conditions, spray nozzles.

## Introduction

Estimates and risk assessments of spray drift have mainly concentrated on drift from the field into horizontal areas such as neighboring fields or water bodies (*e.g.* Ganzelmeier *et al.* 1995[1]). However, experiments simulating pesticide drift have shown that some common berry-producing hedgerow tree species are very sensitive to herbicides. Thus, several studies found that sulfonylurea herbicides reduce growth and fruit yield of cherry trees at dosages as low as 1% of the label rate,[2–4] and Kjær *et al.* (2006)[5,6] showed that drifting metsulfuron methyl may reduce the growth and berry production of hawthorns, both in the year of exposure and in the following year. Since the berries of *e.g.* hawthorn, are not uniformly distributed over the height of the trees, pesticide deposition at different heights may have different effects. Therefore, knowledge of the vertical distribution of pesticides drifting into hedgerows is very important.

Previous measurements of pesticide spray drift have concentrated on soil deposition at varying distances from the spray boom. Most studies have only included one run by the tractor, *i.e.*, no integration of the total drift from spraying an entire field. The main conclusion from these measurements was that most of the pesticide is deposited within the nearest 5 m.[1,7–9] The few studies that have compared cumulative deposition from one and ten runs show that integration of contributions from ten swaths increases spray drift with a factor of 3–10 for horizontal deposition measures.[10–12] The accumulated deposition at a specific position downwind was calculated from the measured deposition from a single swath at varying distances from the sprayer. A previous study that measured pesticide deposition in hedgerows found that between 2 and 20% of the dosage applied in the swath closest to the hedgerow drifted into the hedgerow.[13] This study showed that at heights up to 2 m above ground, 15–20% of the dosage applied in a single swath 6 m from a hedgerow at a boom height of 1.4 m was deposited on drinking straw samplers placed at a distance of 0–4 from the hedgerow, *i.e.*, 2–6 m from the sprayer, which was mounted with Albuz APG 110V nozzles. Wind speed at boom height was measured to be 3.4 to 4.7 m/s. Furthermore, hedgerows have been shown to reduce spray drift to neighboring fields by up to 90% compared to fields without hedgerows.[14–18] At least some of that 90% is likely to be deposited in the hedgerow. These results support the importance of including contributions from all swaths when estimating how pesticides are deposited in hedgerows.

It is the aim of this study to describe the importance of height, distance and weather conditions for the spray drift to hedgerows. In addition, some settings of the spray equipment were varied in order to qualify the discussion of other necessary variables for the assessment of spray drift. The outcome of the experiments may be used for assessing the efficiency of mitigation measures in terms of buffer zones for potentially exposed/

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vulnerable organisms living in different parts of the hedgerows.

## Materials and Methods

A series of seven spray experiments was carried out in order to determine the pesticide deposition in hedgerows due to spray drift from multiple spray swaths. These experiments were conducted so that deposition at different heights of the hedgerow could be determined in order to estimate the effect of an unsprayed buffer zone on spray drift.

The experiments took place in a spring barley field surrounded by hawthorn hedgerows on three sides (west, north and east of the field). In each experiment, spray drift from five swaths with increasing distance to a hawthorn hedgerow was measured individually, and the experiment was repeated on seven occasions (April 2005, May 2005, June 2005, August 2005, September 2005 and twice in June 2010) in the hedgerow approximately perpendicular to the actual wind direction on the day of spraying. The deviations in the seven trials were 3–9°, 3–20°, 6–26°, 23–37°, 19–40°, 23–37° and 11–24°, respectively. The increased drift distances at large deviations from 90° were not taken into account.

### 1. *Spray application*

Spraying was performed with a conventional tractor-mounted sprayer in five tracks parallel to the hedgerow. The employed spray nozzles were Hardi 4110-16 (Hardi, Denmark; comparable to the Hardi ISO 025 or 03 with respect to liquid delivery rate, BCPC class "Fine") in 2005 and TeeJet AI 110-04 (TeeJet, Illinois, USA; BCPC class "Coarse" to "Very Coarse") in 2010. The spray boom was 12 m wide with a nozzle distance and boom height of 50 cm. Thus, distances between the near end of the spray boom and the hedgerow were 0, 12, 24, 36 and 48 m for the different swaths, except for June and August 2005, where the distances between hedgerow and spray boom were 4 m longer due to a 4 m wide dirt road running along the hedgerow. The tractor had a driving speed of 6.4 km/h in 2005 and 7 km/h in 2010 (*cf.* Table 1).

In order to determine spray drift, sodium fluorescein was added to the spray liquid as a tracer dye at concentrations of 1.49, 2.23, 1.63, 1.99, 1.83, 1.93 and 2.23 g/L, respectively. On one occasion (May 2005), the herbicide metsulfuron methyl was applied together with the dye marker sodium fluorescein in order to establish the relationship between herbicide and dye deposition. The concentration of metsulfuron methyl in the spray liquid was 0.02 g/L. At all other spraying events, only the dye was applied, since the dye is both cheaper and easier to analyze.

Meteorological conditions were registered (Table 1) by measuring relative humidity (Theodor Friederichs Humidity Sensor 3030 (Schenefeld, Germany) at 1.3 m height), temperature, wind speed, wind direction, turbulence, heat flux (Metek USA-1 Ultrasonic Anemometer (Elmshorn, Germany) at 4 m height) and global radiation (Soldata SPC80 Pyranometer, Silkeborg, Den-

**Table 1.** Meteorological data and characteristics for spraying equipment for each of the pesticide spray drift trials

| | Parameter, unit | Trial | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | April 05 | May 05 | June 05 | Aug. 05 | Sept. 05 | June 10 | June 10 |
| Environmental Conditions | Crop density | Sparse | Sparse | Dense | Stubbles | Stubbles | Dense | Dense |
| | Crop height, cm | 2 | 5 | 20 | 10 | 10 | 20 | 20 |
| | Hedgerow orientation | West | North | East | East | West | East | East |
| | Wind speed, m/s | 5.5–6.2 | 2.0–3.6 | 2.9–3.8 | 3.7–4.5 | 2.4–3.3 | 4.6–5.8 | 4.8–5.6 |
| | Wind direction, °C | 114–126 | 197–220 | 271–303 | 260–274 | 136–157 | 260–274 | 273–286 |
| | u*, m/s[b] | 0.51–0.61 | 0.19–0.28 | 0.39–0.45 | 0.34–0.53 | 0.29–0.58 | 0.45–0.62 | 0.51–0.61 |
| | L, m[c] | −57–−88 | −5–−21 | −58–−88 | −21–−87 | −24–−107 | 244 | −116–−196 |
| | Heat flux, W/$m^2$ | 206–255 | 51–130 | 74–120 | 93–205 | 91–164 | 44–112 | 85–144 |
| | Temperature, °C | 10–11 | 11–12 | 17–18 | 17–18 | 22–24 | 12–15 | 15–16 |
| | Glob. Rad.[d] W/$m^2$ | 640–700 | 470–440 | 600–750 | 410–490 | 420–480 | 374–895 | 602–920 |
| | Absolute[e] hum., g/kg | 3.6–4.0 | 4.6–4.9 | 8.6–9.1 | 6.4–7.3 | 9.0–10.4 | 6.6–6.8 | 6.6–6.7 |
| Spraying equipment settings | Nozzle type[f] | FF | FF | FF | FF | FF | AI | AI |
| | Pressure, mPa | 0.55 | 0.55 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| | Flow rate, L/min | 1.6 | 1.6 | 1.1 | 1.1 | 1.1 | 1.6 | 1.6 |
| | Speed, km/h | 7 | 7 | 7 | 7 | 7 | 6.4 | 6.4 |
| | Application rate, L/ha | 300 | 300 | 200 | 200 | 200 | 300 | 300 |
| | Tank concentration, g/L | 1.49 | 2.23 | 1.63 | 1.99 | 1.83 | 2.23 | 1.93 |

[a] Relatively thin cloud cover
[b] The parameter u* is the friction velocity, a measure of air turbulence
[c] L (Monin–Obukhov number) is a parameter of atmospheric stability
[d] "Glob.rad." is the global radiation
[e] Calculated on basis of relative humidity, temperature and air pressure
[f] FF=Hardi flat fan 4110-16 nozzles and AI=TeeJet Air induction 110-04

mark). The equipment was mounted on a 6 m high mast placed in the center of the field. Absolute humidity was calculated on the basis of relative humidity, temperature and air pressure, the latter obtained from Deutscher Wetterdienst Offenbach (DWD) at http://www.wetter3.de/Archiv/archiv_dwd.html, with an accuracy of 1 hPa.

### 2. *Characterization of nozzles*

The droplet size distributions of the Hardi 4110-16 flat fan nozzle at 0.30 mPa and 0.55 hPar and the TeeJet air induction nozzle 110-04 at 0.3 mPa were experimentally determined, using the Phase Doppler Particle Analyzers (PDPA) laser-based measurement setup and protocol described by Nuyttens *et al.* (2007, 2009).[19,20] Droplet size and 1D-velocity measurements were performed at 0.05 m below the spray nozzle by scanning a rectangular pattern at a constant speed to achieve a complete scan of the spray plume close to the nozzle exit. All measurements were made using tap water at a temperature of 20°C. Environmental conditions were kept constant at a temperature of 20°C and a relative humidity of 60–70%. Each scan yielded data for at least 20,000 droplets.

### 3. *Spray deposition measures*

For each of the five swaths in a single experiment, herbicide and dye were collected on leaves from the hedgerow and on hair curlers mounted uprightly on five masts placed at 10 m intervals right next to the hedgerow trees (Fig. 1). First the 12 m wide swath closest to the hedgerow was sprayed; thereafter the exposed curlers and leaves were sampled. Then the second swath, placed 12 m farther way from the hedgerow, was sprayed and curlers and leaves collected, and so on until all five swaths had been sprayed and all samples collected. The selection of sampling methods was made to achieve both standardized measures (curlers) and ecologically relevant measures (leaves). Due to the different analysis techniques (see below), herbicide and dye were analyzed on separate samples.

#### 3.1. *Leaf samples*

At the time of the first spraying in April 2005, leaves had not yet emerged. At all other spray events, each leaf sample consisted of 5–10 leaves from a single branch on the "surface" of the hedgerow facing the sprayed field. Samples were taken in the immediate vicinity of the masts carrying the curlers, at app. 0.5, 1 and 2 m above ground with five replicates per height and swath (Figs. 1 and 2). Prior to spraying, all branches selected for sampling were covered with plastic bags (Fig. 2). Just before the spraying of a given swath, the relevant plastic bags were removed in order to ensure that each leaf sample was only exposed to spray drift from that particular spray swath. Immediately upon exposure, the leaves were sampled, placed in plastic cylinders containing extraction fluid (0.1 M $Na_2HPO_4$ buffer or deionized water) and stored in darkness to prevent photo degradation of the dye. In the laboratory, the total one-sided leaf area was determined by means of an LI-3100 Area Meter (LI-Cor. Inc., Nebraska, USA).

#### 3.2. *Curler samples*

Prior to the spraying of a swath, the five masts (replicates) placed in the hedgerow were equipped with two hair curlers (commercial plastic hair curlers of the brand M-cosmetics, diameter 2 cm, length 6 cm) at each height (0.5, 1, 2 and 4 m) in order to measure dye marker deposition (Figs. 1 and 2). In May 2005, when herbicide was applied, one more curler was added at each height on the masts placed in the hedgerow in order to sample herbicide deposition at spraying 0, 24 and 48 m from the hedgerow. Upon spraying, curlers were treated as described for leaves. Results were expressed as the amount of sodium fluorescein per curler as all curlers have the same collection area.

#### 3.3. *Analysis of sodium fluorescein*

Sodium fluorescein deposition was measured by fluorescence spectrophotometry upon extraction in a 0.1 M $Na_2HPO_4$ buffer adjusted to pH 6.8 with $NaH_2PO_4$. Fluorescein is excited at 492 nm and was detected at 513 nm by a fluorescence HPLC monitor (Shimadzu RF-551, Shimadzu, Kyoto, Japan; detection limit 0.01 $\mu$g/L). In addition to leaf and curler samples, a sample from the spray tank was analyzed from every spraying occasion. Prior to the experiments, the potential decay of sodium fluorescein was estimated and no decay could be detected during two days of storage at room temperature, which indicates that no measurable decay took place between sampling and analysis. Since the period of time from when a swath was sprayed until all samples were placed in darkness did not exceed 20 min, the risk of photo degradation in the field is considered negligible.

#### 3.4. *Analysis of metsulfuron methyl*

Metsulfuron methyl was extracted from curlers with deionized water. Chlorsulfuron was added to the water extract as a surrogate standard, since isotope labeled metsulfuron was not available at the time of the experiments. The water extract was further concentrated on solid phase extraction (SPE) cartridges (Oasis HLB, 200 mg, Waters, Milford USA). Detection and quantification of the target compounds were performed with liquid chromatography-tandem mass spectrometry (LC-MS-MS) equipped with electrospray ionization (ESI) operating in positive ionization mode. The analytes were separated on a Hypersil C18 column 2.1×25 cm, 5 $\mu$m particle size (Phenomenex) with 5 mM ammonium acetate buffer and methanol as mobile phase A and B, respectively. The mass spectrometer was operated in multiple reaction monitoring (MRM) for the following precursor-product transition ions: 382/167 for metsulfuron methyl and 358/167 for chlorsulfuron.

Leaf areas (one-sided) were measured by means of a LI-3100 Area Meter (LI-Cor. Inc., Nebraska, USA) before the leaves were cut and crushed in liquid nitrogen. The samples were spiked with chlorsulfuron and mixed with a 25% aqueous solution of methanol (pH adjusted to 12 with sodium hydroxide). This mixture was extracted ultrasonically for 15 min. The resulting extract was filtered through nylon mesh (0.42 and 0.2 $\mu$m) and analysed by LC-MS-MS. The samples were extracted and analyzed in batches together with a procedural blank. The target compounds were not detected in any of the blank samples. The

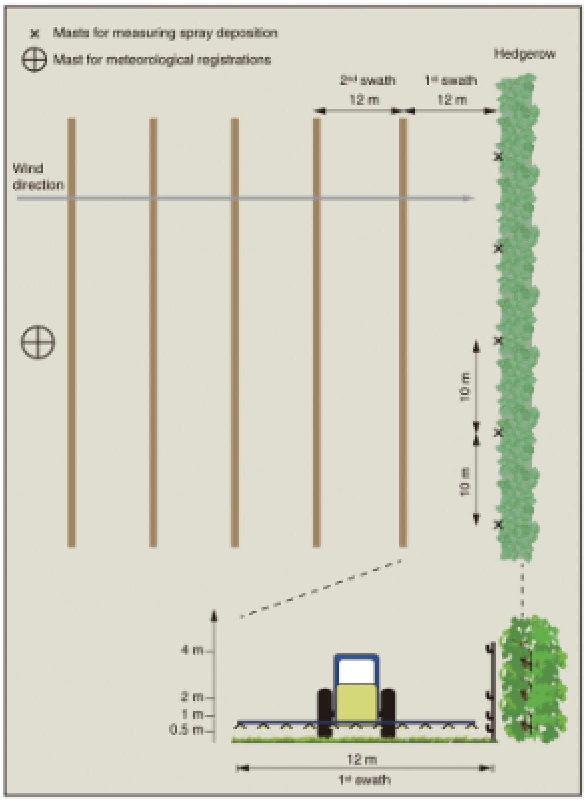

**Fig. 1.** Outline of experimental setup, showing the position of the masts and the swaths sprayed (top) and a close-up of the tractor's position at the spraying of the first swath (bottom).

detection limit of the analytical method (MDL) was defined as those concentrations of the analytes needed to produce a signal-to-noise ratio (*S*/*N*) of 3 : 1.

The detection limit for metsulfuron methyl was 0.8 and 3 ng per sample for curlers and leaves, respectively.

### 3.5. *Buffer zone calculations*

Unsprayed buffer zones have been used as a tool to reduce pesticide drift to surrounding areas, especially to water bodies. In the present study, drift is expressed as estimated area-based deposition on leaves ($\mu$g/cm$^2$ brought to the scale of L/ha) as a percentage of the area-based application rate in the field (L/ha). The actual deposition given in $\mu$L/curler was multiplied by the conversion factor from curler deposition to leaf deposition per area (Table 3) and divided by the actual tank concentration. This gives a deposition equivalent to $\mu$L spray liquid/cm$^2$.

The accumulated deposition was calculated as

$$\text{Accumulated deposition} = \sum \text{Deposition} \times \text{Conversion factor} \times \text{Tank concentration},$$

For calculation of the importance of unsprayed buffer zones for the spray deposition in adjacent habitats (hedgerows), the contributions from three swaths were summed. As only five swaths were established in the experiments, the buffer zones in the calculations have a width of 0, 1 or 2 spray swaths (0, 12 and 24 m for five spray occasions; 4, 16 and 28 m for the two occasions with a dirt road between the field and hedgerow), since wider buffer zones would lead to integration of fewer than three swaths. Consequently, the summation for the scenario without a buffer zone consisted of swaths 1, 2 and 3; in the case of a 12 m buffer zone the summation involved deposition from swaths 2, 3 and 4. The effect of a 24 m buffer zone was calculated on basis of deposition measures from spray swaths 3, 4 and 5.

**Fig. 2.** Photo of mast mounted with curlers and branches covered with plastic bags to avoid untimely exposure. Insert shows closer view of hair curlers on mast.

These calculations were made separately for each trial because the conversion factors differed between experiments. Since there was no conversion factor for the first experiment as the leaves had not yet emerged, the average conversion factor of the other six trials (0.02) was used.

### 4. *Statistical methods*

Linear regression analysis was used to estimate the relationship between measured herbicide deposition and tracer deposition as well as the relationship between tracer deposition on artificial targets (hair curlers) and hawthorn leaves (trial repeated seven times). In each trial, runs with five swaths of increasing distance to sprayer were conducted with sampling five replicates for each of the four sampling heights.

The spray deposition data were analyzed using a multiple model, *i.e.*, a regression model with several explanatory variables (generalized linear models; GLM). The initial statistical model was as follows:

$$\begin{aligned}\text{Log (Deposition)} = {} & \text{Intercept} + \beta_1 \cdot \text{Temperature} \\ & + \beta_2 \cdot \text{Wind speed} + \beta_3 \cdot \text{Absolute humidity} \\ & + \beta_4 \cdot \text{Initial droplet size distribution} \\ & + \beta_5 \cdot \text{Height in hedgerow} + \beta_6 \cdot \text{Distance to hedgerow}\end{aligned}$$

Before estimating the statistical parameters ($\beta_x$), the response variable "deposition" was transformed by the natural logarithmic function, resulting in Gaussian distributed residuals and a multiplicative model on the non-transformed scale of the response variable. To avoid the problem of multi-collinearity in regression analysis, Pearson correlation coefficients were calculated between each pair of continuous explanatory variables. No large correlations (Pearson's correlation coefficients between −0.3 and 0.3) were found, and consequently, all explanatory variables could be included in the primary statistical model. Any non-significant terms were excluded and parameters were re-estimated. As measures of initial droplet size distribution $V_{100}$ (percentage droplets smaller than 100 $\mu$m), $V_{50}$ (percentage droplets smaller than 50 $\mu$m) and VMD (median droplet diameter) were tested.

## Results

The characteristics of the two nozzle types are summarized in Table 2. As expected, the Hardi flat fan nozzle produced smaller droplets than the TeeJet air induction nozzle at equal working pressure (0.30 mPa). Furthermore, increasing the working pressure to 0.55 mPa caused the Hardi nozzle to produce slightly smaller droplets.

The comparison of deposition measures of the herbicide metsulfuron methyl and the dye tracer fluorescein showed that tracer deposition and herbicide deposition measured in separate samples were well correlated (metsulfuron ($\mu$g/curler)=0.01×tracer ($\mu$g/curler) $N=60$, $R^2=0.71$). Since there was a factor of 100 difference in concentration between metsulfuron methyl and fluorescein in the spray liquid, the established relationship between pesticide and tracer means that the rate of deposition on curlers is similar for the two substances. Furthermore, it was found that tracer deposition on hair curlers was significantly correlated to tracer deposition on leaf surfaces in the hawthorn hedgerow (Table 3). However, the relation differs between hedgerows and between days.

Fig. 3 demonstrates that deposition was highly variable between single trials, even though some trials (6 and 7) were conducted in the same place, on the same day and with the same equipment. Further, the subfigures show that deposition depended on distance to sprayer and height in hedgerow. Analysis of the influence of equipment settings and weather conditions showed that initial droplet size distribution, distance of the spray swath to the hedgerow, height of the target in the hedgerow, absolute humidity and wind speed at the time of spraying had significant effects on spray deposition in the hedgerow (Table 4). The resulting statistical model, leaving out temperature and intercept, which turned out not to significantly affect spray drift, and back-transforming the log-transformed deposition data, is:

$$\begin{aligned}\text{Deposition} = {} & \text{Wind speed}^{\beta 2} \cdot \text{Absolute humidity}^{\beta 3} \\ & \times V_{100}{}^{\beta 4} \cdot \text{Height in hedgerow}^{\beta 5} \\ & \times \text{Distance to hedgerow}^{\beta 6} \cdot e^{1.77}\end{aligned}$$

The bias-correction factor needed when back-transforming ($e^{1.77}$) is derived according to Ferguson (1986).[21] All measures of initial droplet size distribution showed the same trend, with $V_{100}$ giving a slightly better description ($R^2$) than $V_{50}$ and VMD. The resulting statistical model described 82% of the observed variation. The F-statistic of the analysis of variance gives the importance of the influential factors. The primary single impact factor was "Distance to hedgerow" followed by "Absolute humidity," "Height in hedgerow," $V_{100}$ and wind speed.

The calculations of accumulated deposition from three spray swaths show that for the Hardi flat fan nozzles (trials 1–5) without a buffer zone, the deposition at a height equivalent to the height of the spray boom varied between 1.5 and 8% of the application rate (solid line in Figs. 4 A–E, height 0.5 m). At a height of 4 m, this was reduced to a deposition between 0.36 and 0.77%.

By introducing a buffer zone of 12 or 24 m, deposition as a function of height was changed so that there were only small differences in deposition with height for the different buffer zones (broken lines in Figs. 4 A–E), which demonstrates that the effect of buffer zones was largest in the lower parts of the hedgerow.

**Table 2.** Droplet size characteristics (avg±S.D.) of the nozzles applied in the field experiments. Bar values indicate working pressure of nozzles. $V_{50}$ ($V_{100}$): proportion of total volume of droplets with a diameter smaller than 50 (100) $\mu$m; VMD: volume median diameter; drops smaller than this diameter make up 50% of the total volume

| | Hardi 4110-16, 0.3 mPa | Hardi 4110-16, 0.55 mPa | TeeJet AI 110-04, 0.3 mPa |
|---|---|---|---|
| $V_{50}$ (%) | 1.00±0.06 | 0.87±0.13 | 0.029±0.001 |
| $V_{100}$ (%) | 8.99±0.73 | 9.99±1.79 | 1.80±0.19 |
| VMD ($\mu$m) | 213.2±8.8 | 198.1±16.4 | 439.4±6.5 |

**Table 3.** Relationship between deposition on hair curlers and deposition on leaf surfaces in the hawthorn hedgerow. The relationship is described by $D_{\text{leaves}}=\alpha \times D_{\text{curlers}}$, where $D_{\text{leaves}}$ is deposition on leaves given in $\mu$g tracer/cm$^2$ and $D_{\text{curlers}}$ is measured deposition on curlers given by $\mu$g tracer/curler. Experiment 1 is not presented as no leaves had emerged at the time of the experiment

| Trial | $\alpha$±S.E. | $N$ | $R^2$ | $F$ | $p$ |
|---|---|---|---|---|---|
| 2 | 0.0307±0.00441 | 69 | 0.42 | 48.29 | <0.0001 |
| 3 | 0.0200±0.00110 | 73 | 0.82 | 335.95 | <0.0001 |
| 4 | 0.0133±0.00086 | 73 | 0.77 | 240.55 | <0.0001 |
| 5 | 0.0186±0.00189 | 69 | 0.59 | 96.91 | <0.0001 |
| 6 | 0.0152±0.00182 | 75 | 0.49 | 69.77 | <0.0001 |
| 7 | 0.0228±0.00130 | 71 | 0.81 | 309.28 | <0.0001 |

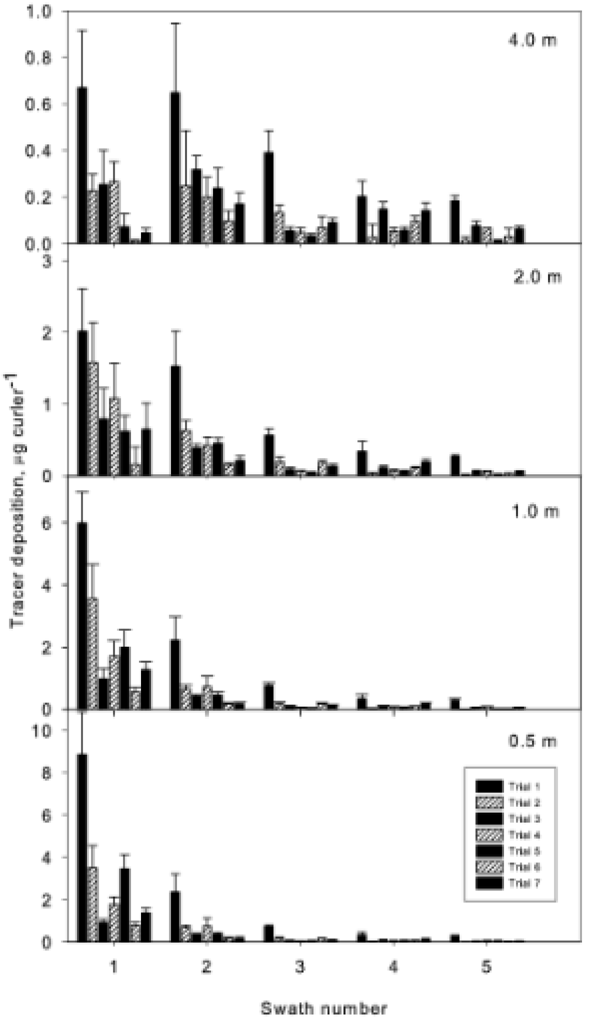

**Fig. 3.** Mean deposition (±Standard Error of Mean) of sodium fluorescein on curlers in the hedgerow following application at varying distances from the hedgerow (spray swaths 1 to 5). Data from seven trials are presented. Each subfigure represents a specific height in the hedgerow. The scales of the *y*-axis differ between subfigures.

The deposition at 4 m height was nearly independent of the establishment of buffer zones as long as the same field area was sprayed. On average (±SEM), depositions at the heights of 0.5, 1, 2 and 4 m were reduced by 72±4, 66±4, 47±8 and 0.15±14%, respectively, by inserting a 12 m wide unsprayed buffer zone between the field and hedgerow. For a 24 m wide buffer zone, the corresponding reductions were 88±3, 85±4, 73±8 and 41±14%.

## Discussion

The present study documents that the level of spray drift is different for different heights in a hedgerow adjacent to a sprayed field and that introduction of an unsprayed buffer zone will have different effects at different heights. This is important because different organisms utilize different parts of the hedgerow for feeding and nesting. Our results are in agreement with Parkin and Merritt (1988),[22] who measured deposition from Lurmark 04-F110 nozzles at heights between 0 and 12 m and found that spray drift from short distances decreased rapidly with height, whereas at longer distances from the sprayer deposition only decreased slightly with height. Weisser *et al.* 2002,[23] who studied the deposition on plant surfaces in a hedgerow, also found decreased deposition from the bottom of the hedgerow up to a 2 m height for both a low-drift nozzle AI 110 025 and the conventional flat fan nozzle (XR 110 03). In one experiment, Longley *et al.* (1997)[13] found only very small differences between 1, 1.5 and 2 m heights when combining data from distances of 2, 4 and 6 m from the spray boom. However, our results demonstrate that drift from longer distances contributes more to the total drift at the top of the hedgerow than to the total drift at the lower part of the hedgerow (Fig. 4). In addition, boom height was 1.4 m in the Longley *et al.* experiment, *i.e.*, not much lower than the highest points of measuring. In another experiment, Longley and Sotherton (1997)[24] found maximum deposition at the height of the spray boom and diminishing values upward.

Taking into account the fact that fluorescein and herbicide were measured on separate curler samples, the former proved a good predictor of the latter, which demonstrates the applicability of dye markers in spray drift experiments. Fluorescein deposition on hair curlers also was a good measure for herbicide deposition on leaf surfaces in hawthorn hedgerows. However, the relation between deposition per curler and deposition per leaf area differed between hedgerows and between days, probably reflecting variation in factors such as leaf development and size, hedgerow porosity and weather conditions.[25,26] However, we have no indications of how collecting efficiency of the curlers depends on meteorological and technical factors.

It is interesting not only how deposition varies with environmental conditions and the setting of the spraying equipment but also whether the observed levels of deposition can evoke detrimental effects on non-target organisms. The effects of drifting insecticides on insects in hedgerows have been studied by Longley and Sotherton (1997),[24] who found that a single swath of 10 m caused a 25% mortality rate for second instar *Spodoptera littoralis*, Boisd. larvae. Similarly, Cilgi and Jepson (1995)[27] found an expected mortality rate of 75% from deltamethrin for fourth instar larvae of *Pieris brassicae* L. (Lepidoptera, Pieridae) at levels comparable to 0.01–2% of field rate, *i.e.*, at exposure levels that according to our results are very likely to occur in hedgerows. Thus, insecticide effects from drift into hedgerows may occur.

For plants, several studies have assessed the impact of sulfonylurea herbicides on berry.producing trees, *i.g.*, bird cherries, sweet cherry and hawthorn.[2,5,6] Al-Khatib *et al.* (1992)[2] found a 13–60% effect for different end points at a dose of 3% of the field rate. Kjær *et al.* (2006)[6] demonstrated nearly 100% mortality at exposure levels observed at spray drift under normal spray conditions (2.5–5% of maximum recommended field rate) and Kjær *et al.* (2006)[5] found that reproduction was still affected a year after exposure at an exposure of 10% of the maximum recommended field rate. Consequently, the drift rates measured in the

**Table 4.** Multiple regression model with several explanatory variables for spray deposition in hedgerows. Before estimating the model, the response variable "Deposition" was transformed by the natural logarithmic function resulting in Gaussian distributed residuals and a multiplicative model on the original scale of the response variable

| Effect (parameter) | Parameter estimate | $F$ | $N$ | $DF$ | $p$ | $R^2$ |
|---|---|---|---|---|---|---|
| Model | | 747.43 | 801 | 5 | <0.0001 | 0.824 |
| Wind speed ($\beta_2$) | −1.44 | 31.46 | | | <0.0001 | |
| Absolute humidity ($\beta_3$) | 0.279 | 124.64 | | | <0.0001 | |
| $V_{100}$ ($\beta_4$) | −0.0636 | 80.12 | | | <0.0001 | |
| Height in hedgerow ($\beta_5$) | −0.270 | 112.35 | | | <0.0001 | |
| Distance to hedgerow ($\beta_6$) | −0.0472 | 679.91 | | | <0.0001 | |

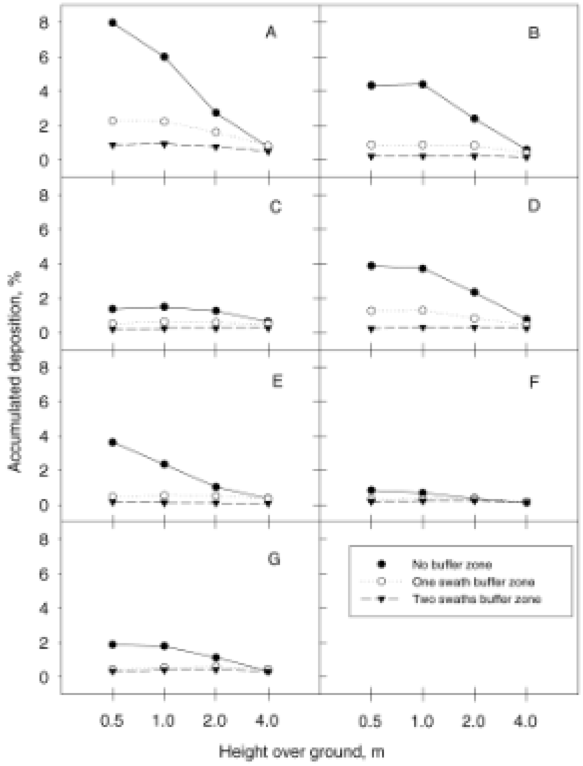

**Fig. 4.** Effect of unsprayed buffer zones on accumulated spray drift from three spray swaths in a hedgerow. The different graph lines represent the calculations without a buffer zone, with a 12 m buffer zone and with a buffer zone of 24 m. The $y$-axes give the deposition relative to application rate. In 2005 the distance between the hedgerow and the spray boom was 4 m longer for the east hedgerow due to a dirt road running along the hedgerow (subfigures C and D). Each subfigure presents data from single spray events given by the following summary details (trial number, wind speed, hedgerow orientation, nozzle type, and date of spraying): A: Trial 1, 5.5–6.2 m/s, West, Hardi, April; B: Trial 2, 2.0–3.6 m/s, North, Hardi, May; C: Trial 3, 2.9–3.8 m/s, East, Hardi, June; D: Trial 4, 3.7–4.5 m/s, East, Hardi, August; E: Trial 5, 2.4–3.3 m/s, West, Hardi, April; F: Trial 6, 4.6–5.8 m/s, East, TeeJet, June; G: Trial 7, 4.8–5.6 m/s, East, TeeJet, June.

present experiment are also likely to cause effects on hedgerow plants, at least for some herbicides.

In order to assess the risk of effects of spray drift on hedgerow plants or other organisms living in the hedgerows, it is necessary to be able to predict the spray deposition under the conditions most relevant for the area of concern and to be able to differentiate between organisms living at different heights in the hedgerow. Unsprayed buffer zones are used as mitigating measures to reduce deposition outside the cropped area.[8] The background for this practice is spray drift assessments developed for water bodies and measured by means of targets placed horizontally at a low height. The fact that unsprayed buffer zones will have a large effect on spray drift at the bottom of the hedgerow, but only small or even negligible effects on drift at the upper part, strongly indicates that buffer zones are a useful mitigation measure for organisms living in the lower parts but not necessarily for those living at the top of the hedgerow. Therefore, protection of hedgerows and other habitats with a significant vertical component may require other measures such as drift-reducing nozzles and careful choice of spraying conditions. For hedgerow trees, this need is further heightened by the fact that many species carry the majority of their flowers and berries in the top part.

We found that both weather conditions and initial droplet size distribution as affected by the type and pressure of nozzles were important for the size of the deposition in the hedgerow. Thus, in our experiments the primary impact factor was distance to hedgerow followed by absolute humidity, height in hedgerow, percentage of droplets smaller than 100 $\mu$m and wind speed. Another study[24] has also shown that weather conditions such as wind speed are important. Arvidsson *et al.* (2011)[28] measured both horizontal fallout and airborne drift at a distance of 5 m from the sprayer. They found a correlation between pesticide deposition and wind, temperature, driving speed, and vapour pressure deficit. Our experiments show that deposition in trials employing low-drift nozzles (TeeJet) are generally lower than that in trials using flat fan nozzles. The AI nozzle is registered as a 50–75% drift-reducing nozzle in Germany. In Weisser's experiments,[23] the reduction was even larger. The AI nozzle in general produces larger droplets than the Hardi nozzle. Therefore, a large part of the spray liquid is expected to sediment, and less pesticide is available for spray drift. This is underlined by Nuyttens *et al.* (2007)[19,29] and many others[1,11,12,30] who have studied the effect of equipment and equipment setting, primarily on horizontal deposition. As an example, it has repeatedly been shown that different nozzle types give rise to different depositions, which is in line with our results for the two nozzle types employed in the present study.

It is known that spray drift is closely related to the droplet size distribution of the spray,[31) and this is sustained by the significant influence of initial droplet size on spray drift found in this project. Several factors may affect droplet size, including nozzle type, nozzle pressure and temperature.[19) Therefore, it seems reasonable to suggest that a more general description of spray drift can be based on the formation and behavior of different droplet size classes under varying environmental conditions. Droplet size characteristics can be obtained under controlled conditions in wind tunnels or in environmentally controlled chambers, as done in this project and described by Nuyttens *et al.* (2009).[32) However, such measurements do not take the effects of turbulence and other weather conditions into account. This factor is implicitly included in experiments such as the one described in the present project, which is one of the reasons field experiments cannot be entirely substituted with laboratory experiments.

Generally, spray drift experiments have a high variance between samples from the same positions, as described in Arvidsson.[28) However, the fact that the statistical model established in this study describes 82% of the variance among samples from five field trials suggests that many of the most important factors have been included in the model and that it may be worthwhile to try to account for the remaining variation.

In the calculation of the deposition in the hedgerow, we used the accumulated deposition from three spray swaths (36 m); however, under normal conditions this is not sufficient, since fields are usually much wider. For instance, in Denmark the average field size is approximately 4 ha.[33) Therefore, it is important to be able to predict the contribution from more spray swaths in order to make trustworthy risk assessments, and the present study has shown that at least five spray swaths (60 m) add significantly to the total deposition, especially at the top part of the hedgerow.

Several aspects concerning spray drift have not been covered by the present project but should be included in future estimates of spray drift, *e.g.* other types of pesticides, additives, other types of spraying equipment (air-assisted sprayers in particular), and hedgerow characteristics such as species composition and porosity.

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## Bilag 2: The OML-SprayDrift model for predicting pesticide drift and deposition from ground boom sprayers

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**Original Article**

# The OML-SprayDrift model for predicting pesticide drift and deposition from ground boom sprayers

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In order to predict the exposure of hedgerows and other neighboring biotopes to pesticides from field-spray applications, an existing Gaussian atmospheric dispersion and deposition model was developed to model the changes in droplet size due to evaporation affecting the deposition velocity. The Gaussian tilting plume principle was applied inside the stayed track. The model was developed on one set of field experiments using a flat-fan nozzle and validated against another set of field experiments using an air-induction nozzle. The vertical spray-drift profile was measured using hair curlers at increasing distances. The vertical concentration profile downwind has a maximum just above the ground in our observations and calculations. The model accounts for the meteorological conditions, droplet ejection velocity and size spectrum. Model validation led to an $R^2$ value of 0.78, and 91% of the calculated drift values were within a factor of four of the measurements.

*Keywords:* spray drift, evaporation, dispersion, deposition, pesticide.

**Electronic supplementary materials:** The online version of this article contains supplementary materials (Supplemental Materials, Supplemental Tables S1 and S2), which is available at http://www.jstage.jst.go.jp/browse/jpestics/.

## Introduction

Pesticide drift during field application to sensitive neighboring non-target biotopes or biotopes between fields is of much interest and has potential impacts on human health and livestock.[1–3] Several mechanistic models have been developed to predict the drift, deposition, and air concentrations of pesticides from various types of application equipment in order to understand the physical basics of spray drift as well as to develop a tool for regulatory assessment of unintended off-target exposure. However, the main concern has been habitats with no significant vertical component, *e.g.*, water bodies.

Different types of model approaches have been taken all with advantages and disadvantages: Computational Fluid Dynamics (CFD) models,[4] random-walk trajectory models,[5–9] diffusion-advection models,[10] and Gaussian tilting plume models.[11,12]

CFD models can calculate the complicated flow and dispersion close to nozzles and spray equipment. These models are typically applied for distances up to 5 m, implying that they do not account for the cumulative effect of the numerous spray tracks farther away from the field edge. The cumulative effect is important, particularly for the vertical concentration profile and deposition to *e.g.*, hedgerows. CFD models require expert skills, take much time to set up, are computationally demanding,[4] and are not suitable for fast and practical regulatory purposes,[9,12] but software[13] exists to quickly search tables produced from CFD calculations based on fixed turbulence intensity.

Trajectory models can deal with longer drift distances than CFD models, but they are still quite computationally expensive, particularly for longer distances where a large number of released droplets are needed in order to avoid discontinuities in deposition.[11] These models either do not take atmospheric stability into account[6–8] or are calibrated to a particular atmospheric situation.[9] In addition, some models disregard the effects of evaporation of the droplets.[9]

Gaussian tilting plume models are not directly able to model the special effects around the boom and nozzles, but they have the advantage of being easier to set up than CFD models. Gaussian models are more computationally efficient at longer distances than CFD and trajectory models[9] and are therefore favorable for management systems. A major disadvantage of tilting plume models without reflection at the ground is that when the water evaporates from the droplets and they become very small

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or even are reduced to dry pesticide particles, the terminal speed becomes almost zero and the calculated deposition almost stops. In reality, the atmospheric turbulence still maintains the deposition. This could explain the underestimation at the longest distances (20–30 m) of the tilting plume model by Lebeau *et al.*,[12] especially for low wind conditions, where the droplets have a long time to evaporate.

Another way of calculating deposition, commonly used in regional and local dispersion models, is based on the principle that deposition is directly proportional to the concentration at some reference height above the ground. The proportionality constant is called the deposition velocity,[14] $v_d$. The deposition velocity is calculated using the resistance method that, among other parameters, depends on the droplet fall speed and the atmospheric turbulence. This principle will ensure deposition in Gaussian plume models, also at far distances, even when the droplet terminal speed approaches zero. This method is used in the OML-SprayDrift model described in this paper. The model is developed in order to make a fast and easily usable tool for estimation of primary horizontal drift of pesticide application to hedgerows and is intended for use by authorities and agricultural advisors.

## Materials and Methods

### 1. *Spray-drift model*

The OML-SprayDrift model (Operationelle Meteorologiske Luftkvalitetsmodeller, meaning Operational Meteorological Air Quality Model) is a combination of two Gaussian model principles. The Gaussian tilting plume method[11,12] determines the amount of spray deposited inside the directly sprayed zone. The remainder spray is treated as area sources located in the track and is dispersed applying a traditionally reflected Gaussian plume and the deposition beyond the track is calculated by deposition velocity. The model calculates the water and possible pesticide evaporation from the droplets and the resulting change in diameter and vertical velocity as a function of travel distance. Deposition outside the track is converted to negative surface sources following the principle of surface depletion described by Horst.[15] The negative surface sources ensure that the calculated vertical profiles of the horizontal drift at some distance from the edge of the field have a maximum above the ground, which also has been observed and modeled.[9] The model operates on droplet classes in size intervals of 10 $\mu$m.

### 1.1. *Dispersion*

The dispersion model is based on the Danish Gaussian plume model OML, which calculates the atmospheric dispersion of pollutants from multiple point and area sources and has been validated against many different datasets including non-buoyant surface releases.[16] The model is a regulatory model used by the Danish authorities, consultants, and industry. In OML, turbulence is described as continuous functions of micrometeorological parameters like friction velocity, heat flux from the surface, aerodynamic roughness, and the Monin–Obukhov length describing the atmospheric stability. The vertical and horizontal dispersion from a point source is described as a Gaussian (normal) distribution. For a point source placed at coordinates (0, 0, $H$) (m), the concentration $c$ (g m$^{-3}$) at the point ($x$, $y$, $z$) is calculated disregarding deposition as follows:

$$c(x,y,z)=\frac{Q}{2\pi u\sigma_z\sigma_y}\exp\left(-0.5\left(\frac{y}{\sigma_y}\right)^2\right)\times\left(\exp\left(-0.5\left(\frac{z-H}{\sigma_z}\right)^2\right)+\text{reflection terms}\right)$$

where $Q$ is the emission rate (g sec$^{-1}$), $u$ is the wind speed (m sec$^{-1}$), $H$ is the height of the source (m), and $\sigma_y$ and $\sigma_z$ are the horizontal and vertical dispersion parameters (m), respectively. The reflection terms refer to the reflection from the ground surface of the plume and are active outside the track in the OML-SprayDrift model. In most cases, spray drift is a two-dimensional phenomenon, because the long spray track will smooth out the horizontal dispersion when estimating the average concentration. Therefore, the OML-SprayDrift model disregards the horizontal influence and is a 2D model.

### 1.2. *Deposition inside the track*

Inside the spray track, deposition is calculated using a Gaussian tilting plume or settling plume principle.[11,12] The height of the droplet plume centerline, $H$, in the concentration equation is decreased due to the descending droplets. The principle is applied to a number of droplet size classes. In this study, the classes consist of 10 $\mu$m droplet diameter intervals and are in the calculations represented by the median diameter of the interval center. In this case, the theoretical dispersion is not affected by the presence of the ground surface, and the plume is allowed to disperse under the surface; *i.e.*, the reflection term in the concentration equation is neglected. At a given distance, the total deposition is equal to the part of the plume that is located beneath the surface.

The average deposition inside a track is represented by the droplets released at the center of the boom. At the edge of the boom, the deposition for each droplet class is calculated with the tilting plume where the vertical position of the droplet is calculated by the droplet model described in Section 1.4, taking into account the droplet exit speed from the nozzle, the evaporation, and the change in droplet size and speed.

### 1.3. *Deposition beyond the track*

After droplet release, the speed of the smaller droplets reaches a terminal speed within a few tenths of a second, which is not affected by the nozzle exit speed, but for boom heights of 0.5 m, the larger droplets will deposit inside the track. The smaller droplets, which will mainly deposit outside the track, have a terminal speed that is comparable to or less than the typical speed of turbulence eddies, *i.e.*, in order of the friction velocity, $u_*$. This means that the rate of deposition due to turbulent transport will be comparable to the rate of deposition due to pure sedimentation.

The OML-SprayDrift takes this turbulent deposition into account using the surface depletion principle.[15] Deposition at a given distance downwind from a source is handled as a negative source with the same strength as the deposition rate.

The deposition rate *Dep* is calculated based on the principle of deposition velocity $v_d$. The deposition is proportional to the deposition velocity $v_d(z)$ and the concentration $c(z)$:

$$Dep = v_d(z)c(z),$$

where $z$ is the reference height, which is set to 0.5 m in the spray-drift model. The deposition velocity is parameterized analogous to electrical resistances and the dry deposition velocity of particles or droplets[14]:

$$v_d = \frac{1}{r_a + r_b + r_a \cdot r_b \cdot v_s} + v_s,$$

where $v_s$ is the settling velocity of the drop as a function of its diameter, $r_a$ (sec m$^{-1}$) is the aerodynamic resistance, and $r_b$ is the laminar sublayer resistance close to the surface. The aerodynamic resistance in the mixing layer is defined as

$$r_a = \frac{1}{\kappa \cdot u_*} \ln\left(\frac{z}{z_0}\right) - \psi\left(\frac{z}{L}\right) + \left(\frac{z_0}{L}\right),$$

where $\kappa$ is the dimensionless von Karman's constant, $u_*$ (m/sec) is the friction velocity, $z_0$ (m) is the roughness length, and $\psi$ is Businger's corrections function for atmospheric stability.[17]

For particles, the laminar sublayer resistance close to the surface is given as

$$r_b = \frac{1}{u_*(Sc^{-2/3} + 10^{-3/St})},$$

where $Sc$ is the dimensionless Schmidt number: $\nu/D$, where $D$ is the diffusivity, $\nu$ is the kinematic viscosity, and $St$ is the dimensionless Stoke number: $(u_*^2 v_s)/(g\nu)$, where $g$ is gravity (m sec$^{-2}$). The settling velocity of the droplets is incorporated in the Stoke number.

### *1.4. Evaporation and fall velocity of droplets*

The dispersion and deposition model is coupled with a droplet model describing droplet evaporation and the resulting changes in size and velocity. The model takes into account the droplet ejection velocity as well as the relative humidity and ambient temperature. The model is based on a model for pure water and further developed to deal with the pesticide content of the droplet and its possible evaporation. The model assumes no interaction between droplets and that the droplets have no influence on the air. The model does not take formulations and adjuvants into consideration, although it is known that formulations and adjuvants can influence the droplet size distribution[18–20] and thereby affect the drift potential. Although the results of Sanderson *et al.*[21] were related to specific experimental and meteorological conditions, they concluded that drift is considerably lower using water-dispersible granules or liquid-flowable formulations of Propanil compared to emulsifiable concentrates. Chapple *et al.*[22] tested different adjuvants and found that six out of seven adjuvants shifted the droplet spectra relative to water, either to smaller or larger diameters.

The model describes droplet behavior after ejection. A droplet is affected by gravity, the drag force of the air, and the evaporation of water and pesticide. Fall velocity and evaporation are described by solving mass, moment and energy equations for a single droplet. These equations are transformed to equations for diameter, fall velocity, and temperature, respectively. Together with the ambient temperature and relative humidity, these equations determine the exchange and thereby the changes in size, velocity, and temperature of the droplet. A detailed description of the droplet model is found in Supplemental Material.

Droplet fall velocity is an important parameter for the deposition rate to the ground surface and primarily depends on the diameter. Even though the droplet exit speed at the nozzle outlet is in the range of about 15–25 m/sec,[23] the smallest droplet reaches a much lower terminal velocity within a few tenths of a second after exit. However, a continued change in diameter and velocity occurs due to evaporation. For the smallest droplets, the change can be fast, as shown in Fig. 1. For a given diameter, the relative humidity of the air is the most important parameter for the evaporation rate, as shown in the figure.

When the droplets contain a pesticide with a low vapor pressure, the evaporation and change in diameter of the droplets almost stop, and they reach a minimum diameter. This occurs when the relative water content equals the relative humidity of the air. If the pesticide also evaporates, the minimum diameter decreases accordingly.

### *1.5. Calibration and validation*

The model was calibrated and validated against the field measurements described in the next section. The field data were divided into data from the years 2005 and 2010, where a standard flat-fan and an air-injection nozzle were used, respectively. Calibration was performed using the 2005 data and validation

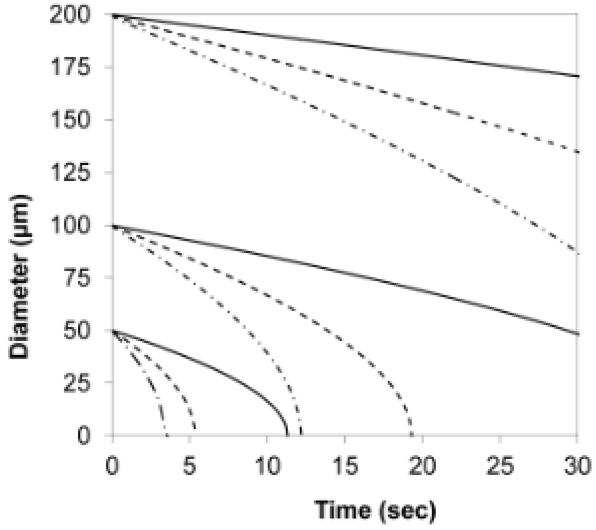

**Fig. 1.** The rate of change in water droplet diameter as a function of initial size of 50, 100, and 200 $\mu$m for different values of relative humidity (full line 80%, broken line 60%, and dot-dash line 40%). Air temperature is 20°C and droplet initial speed is 20 m/sec.

was done on the 2010 data. Many spray-drift models have been calibrated, *e.g.*, using field canopy porosity and velocity scaling parameters,[9)] fitting horizontal and vertical eddy diffusivities $K_y$ and $K_z$ to the first trail in a series,[12)] or adding empirical corrections to the evaporation rate that changed the deposition downwind with a factor of 2.[6)] Teske *et al.*[7)] describe the great variance between different empirical parameterizations of the nozzle-induced airstream velocity due to the entrainment of air. In this study, the calibration also involves the effects of the nozzle-induced airstream.

Calibration was based on the deposition inside the spray track. The droplet model only handles single droplets and does not take into account the effect of the whole continuous spray cloud on the airstream close to the nozzle. A droplet transfers momentum to the surrounding air and is slowed down. The droplet reaches the terminal speed at a certain fall distance, but all the droplets in the spray cloud together create a downward airstream that increases the fall distance compared to the calculated fall distance for a single droplet. Therefore, an algorithm for the empirical additional fall distance is established based on the 2005 data. It is anticipated that a high wind speed destroys the induced airstream. The additional fall distance, $\Delta z$ ($m$), is a function of the wind speed at boom height $u_B$ (m sec$^{-1}$):

$$\Delta z = -0.5u_B + 2.2.$$

The algorithm is applied for $u_B$ below 4.4 m sec$^{-1}$, and $\Delta z$ is 0 m for larger $u_B$, where $u_B$ is calculated from the meteorological observations taking into account the atmospheric stability using Businger's corrections[16)] to the neutral logarithmic wind profile.

### *1.6. Model input and output*

As input, the model needs meteorological information on wind direction, friction velocity (turbulence), Monin–Obukhov length (atmospheric stability), aerodynamic roughness, temperature, humidity, mixing height and boom height. The nozzle droplet spectra and ejection velocity are also needed together with pesticide tank concentration and application rate (L ha$^{-1}$). Driving speed is assumed to be around 7 km hr$^{-1}$.

The model calculates the ground-surface deposition and the vertical profile of the horizontal pesticide flux, in principle, at any distance downwind of any field size. Also, the droplet spectra can be calculated at any position.

## *2. Measurements*

Most spray models are developed using deposition measurements. This type of measurement can be difficult to perform properly in order to measure the far-field drift deposition of small droplets using smooth horizontal surfaces, such as alpha-cellulose sheets, on a rough field surface.[8,11)] To avoid this problem, this study measured the vertical profile of the horizontal drift. In the far field, the total amount of collected spray drift will be much larger than the horizontally deposited spray drift measured per unit area, which reduces uncertainty in measurements.

### *2.1. Field measurements*

A series of spray experiments were carried out in order to determine pesticide droplet dispersion from spray tracks. These experiments were conducted so that horizontal flux at different heights and different distances from the spray boom was determined[24,25)] using sodium fluorescein as a tracer. The tracer is assumed not to evaporate and has a molar mass of 376.3 g mol$^{-1}$, which is about the value of many pesticides.

Spraying was performed with a conventional tractor-mounted sprayer. Spray nozzles were either Hardi 4110-16 (flat fan; Hardi, Denmark) or TeeJet AI 110-04 (air induction; TeeJet, USA). The spray boom was 12 m wide with 24 nozzles, and boom height was adjusted to 50 cm above the vegetation. The tractor driving speed was about 7 km hr$^{-1}$. The conditions for each spraying are presented in Table 1. Before calibration and validation, all measurements were normalized to the same application rate, *i.e.*, 300 L ha$^{-1}$ and 1.49 g L$^{-1}$.

The experiments took place along a hawthorn hedgerow on seven occasions (April 2005, May 2005, June 2005, August 2005, September 2005, and twice in June 2010). The meteorological conditions for wind speed, wind direction, turbulence, temperature, and heat flux were measured with an ultrasonic anemometer at 4 m height on a mast in the center of the 200 m×200 m field, *i.e.*, 100 m from the hedgerow. Relative humidity was also measured (Table 1). The calculated meteorological data during the individual trails are based on 10-min averages in correspondence with Bird *et al.*[8)]

Measurements were performed for five spray tracks parallel to the hedgerow with an increasing distance from the hedgerow (*cf.* Fig. 2). The hedgerow consisted almost entirely of hawthorn (Cartages laevigata (Poiret)) trees about 4–5 m high and 1–2 m wide, with a few gaps. Hawthorn is deciduous, and in Denmark leafing occurs in early May, flowering in May/June. Measurements of the vertical wind profile at 4 positions (1.0, 2.0, 3.5, and 5.1 m above the ground) in the hedgerow were compared with the wind measurements about 100 m upstream at the open field. These measurements indicated that the total horizontal flux from ground to 5.1 m was reduced by about 10% (data not shown). This indicates a small vertical component in the mean flow and is consistent with a measured average vertical wind component at 5.1 m of 8–9% of the horizontal component. Compared to other uncertainties, this is only a minor violation of the implicit assumption of horizontal mean flow.

Spray drift was collected using commercial plastic hair curlers (M-cosmetics, Denmark) mounted on masts 0.5, 1, 2, and 4 m above the ground. The curlers were covered with 3-mm-long "hair," 0.15 mm in diameter, and were assumed to collect droplets with a diameter down to 10 $\mu$m and an effective crosswind area of 2 cm×6 cm. These assumptions were associated with some uncertainty due to the complex structure of the curler.

The masts were placed at five different distances to a hedgerow almost perpendicular to the wind direction. The mast spacing was 12 m, corresponding to the width of the spray boom. At each distance, five masts were set up at 10 m intervals, and the

**Table 1.** Meteorological conditions and settings for the spray equipment during spray events

| | Parameter, unit | Trial | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | April 05 | May 05 | June 05 | Aug. 05 | Sept. 05 | June 10 | June 10 |
| Environmental conditions | Wind speed, m $sec^{-1}$ | 5.5–6.2 | 2.0–3.6 | 2.9–3.8 | 3.7–4.5 | 2.4–3.3 | 4.6–5.8 | 4.8–5.6 |
| | $u^*$, m $s^{-1}$ [a] | 0.51–0.61 | 0.19–0.28 | 0.39–0.45 | 0.34–0.53 | 0.29–0.58 | 0.45–0.62 | 0.51–0.61 |
| | $L$, m[b] | −57–−88 | −5–−21 | −58–−88 | −21–−87 | −24–−107 | 244 | −116–−196 |
| | Heat flux, W $m^{-2}$ | 206–255 | 51–130 | 74–120 | 93–205 | 91–164 | 44–112 | 85–144 |
| | Temperature, °C | 10–11 | 11–12 | 17–18 | 17–18 | 22–24 | 12–15 | 15–16 |
| | RH, % | 42–50 | 53–59 | 65–79 | 47–60 | 45–65 | 67–77 | 63–65 |
| Spraying equipment settings | Nozzle type[c] | FF | FF | FF | FF | FF | AI | AI |
| | Pressure, MPa | 0.55 | 0.55 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| | Flow rate, L $min^{-1}$ | 1.6 | 1.6 | 1.1 | 1.1 | 1.1 | 1.6 | 1.6 |
| | VDM[d], $\mu$m | 198 | 198 | 213 | 213 | 213 | 439 | 439 |
| | Drop ejection speed[e], m $sec^{-1}$ | 18.0 | 18.0 | 15.5 | 15.5 | 15.5 | 9.2 | 9.2 |
| | Tractor speed, km $hr^{-1}$ | 7 | 7 | 7 | 7 | 7 | 6.4 | 6.4 |
| | Application rate, L $ha^{-1}$ | 300 | 300 | 200 | 200 | 200 | 300 | 300 |
| | Tank concentration, g $L^{-1}$ | 1.49 | 2.23 | 1.63 | 1.99 | 1.83 | 2.23 | 1.93 |

[a] The parameter u* is the friction velocity, a measure of air turbulence. [b] L (Monin–Obukhov number) is a parameter of atmospheric stability. [c] FF=Hardi flat fan 4110-16 nozzles and AI=TeeJet Air Injection −110-04. [d] Volume median diameter from measurement in laboratory. [e] Value from centre of measured volumetric droplet velocity distribution from continuous scan in laboratory.

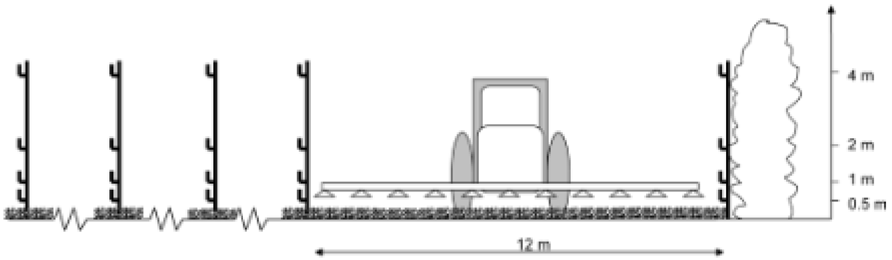

**Fig. 2.** Sketch of the setup of the spray-drift trails for vertical profile measurements with tractor-carried boom sprayer and location of hedgerow and masts with height position of curlers. The masts are positioned in five rows with 12 m in between and with five masts in each row, totaling 25 masts.

first row was placed just in front of the hedgerow, resulting in a total of 25 masts. In each mast, two hair curlers were placed upright at each of the four four sampling heights, giving 10 curler measurements at each height at each distance that were averaged and used in the model calibration and validation. Before spraying the next track, a new row of masts mounted with curlers was erected. In order to reduce the large variability in the measurements, some extra trails were performed where the tractor drove back and forth 10 times in the third track 24 m away from the hedgerow, and measurements were only made in the hedgerow.

*2.2. Droplet size distributions*

Three different droplet size distributions were applied during the field experiments, *i.e.*, the standard flat-fan Hardi 4110-16 at 0.30 and 0.55 MPa and the TeeJet air-induction nozzle 110-04 at 0.30 MPa. The nozzle droplet spectra were experimentally determined using the PDPA laser-based measurement setup and protocol.[26,27] Cumulative droplet size distributions are shown in Fig. 3 together with the results of the flat-fan nozzle XR 110-02 at 0.30 MPa[28] used for the sensitivity analysis in a later section.

## Results and Discussion

*1. Calibration*

The calibration of the model was performed using data from the Hardi flat-fan 4110-16 nozzle spray experiments. As mentioned, the calibration was performed by adding an extra initial fall distance to the distance calculated by the droplet model. The wind speed at boom height was used as a scaling parameter. Calibration tests were performed replacing the measured wind speed with the relative wind speed at the moving boom by combining the driving velocity and the wind velocity. This did not improve the calibration. Baetens *et al.*[4] found only little influence by the tractor speed. This indicates that the turbulence related to the average wind speed might be the most important factor for low driving speeds.

The performance of the OML-SprayDrift model on the dependent data from 2005 is shown in Fig. 4. The values are shown on a log scale in order to differentiate between the smallest values. A group of points marked with a cross in a diamond indicates where modeled values are much lower than the measurements. These points all relate to measurements at 4 m height

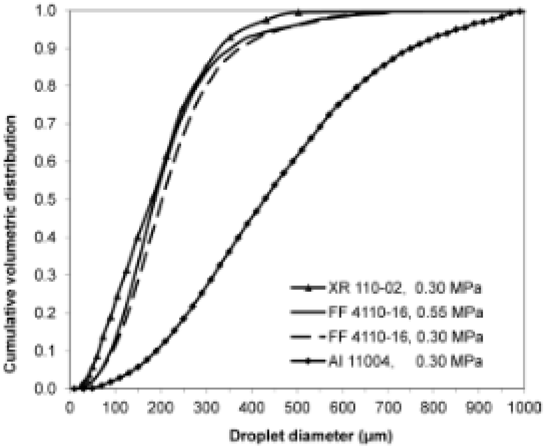

**Fig. 3.** Measured drop spectra for the Hardi 4110-16 standard flat-fan nozzle (at 0.30 and 0.55 MPa), the TeeJet AI 110-04 air-inclusion nozzle (at 0.30 MPa), and the TeeJet XR 110-02 (at 0.30 MPa). Data for XR 110-02 are from Klein and Golus (2004).

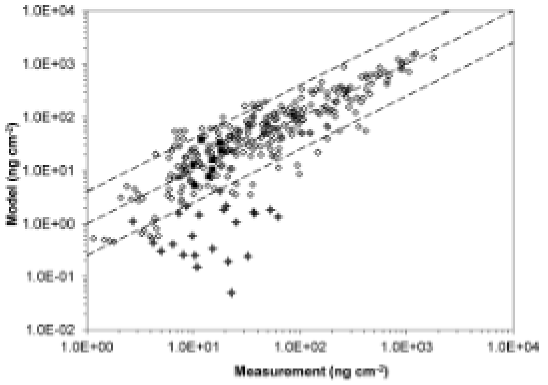

**Fig. 4.** Measured and modeled values of horizontal drift (ng cm$^{-2}$) on data from 2005. Diamonds are single trail values (average of 10 curlers) and solid squares are averages of 10 sprays in the same track, giving a better ensemble average. The diamonds with a cross are for positions 0 m from boom and at a height of 4 m. The central line is the 1–1 curve, and the two others are a factor of four offset.

next to the boom at 0 m distance. The large difference may be due to the wake from the tractor that catches some of the spray and rapidly spreads it to a greater height. This phenomenon is not yet covered by the model. Except for this group of data, there is a reasonably good correlation between measured and model values for both near (high values) and far drift distances (low values). The points of 10 track averages (24 m distance) are, of course, less scattered. For all points, 82% are within a factor of four. This is actually quite good, taking into account that the model predicts deposition values based on 10-min meteorological data, while a spray experiment only represents about 30 sec (total time for 10 curlers collecting droplets passing by in about 3 sec from a 12 m boom in a wind speed of about 4 m sec$^{-1}$).

### 2. *Validation*

The model validation was done for the nozzle TeeJet air-injection 110-04 with a coarser droplet size spectrum (Fig. 3) with fewer small droplets than the Hardi flat-fan 4110-16 nozzle. The comparison between the modeled and measured values is shown in Fig. 5. Again, the group of points with a cross in a diamond represents measurements at 4 m height next to the boom, for which the modeled values are much too low. The explanation is again the effect of the tractor wake rapidly sending droplets upwards. For the other positions, the model performs well, with a tendency to overpredict the lower deposition values. The number of points within a factor of four is improved to 91%. The fact that the validation is performed with a completely different nozzle strengthens confidence in the model.

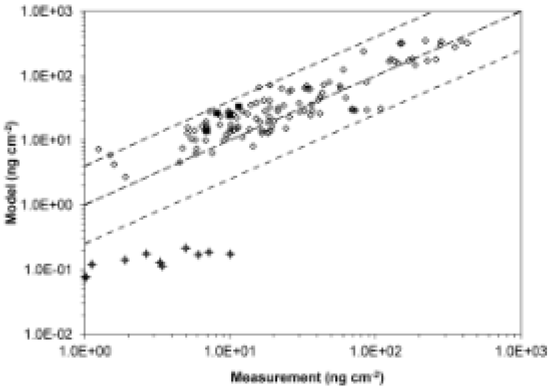

**Fig. 5.** Measured and modeled values of horizontal flux (ng cm$^{-2}$). Validation on independent data from 2010. Crosses are for positions 0 m from boom and at a height of 4 m. See text with Fig. 4 for further explanation.

It is important to notice that the validation is performed for an air-injection nozzle using a model in which the additional droplet fall distance due to the airstream close to the nozzle is calibrated to a standard flat-fan nozzle. Teske *et al.*[7] used two different calibrations of the nozzle induced air stream for these two types of nozzles.

### 3. *Sensitivity*

In order to analyze the model behavior and identify important parameters affecting pesticide drift, some sensitivity runs have been performed, varying one parameter and keeping the others constant if nothing else is mentioned. The calculations were performed for multiple spray tracks of metsulfuron-methyl on a 240 m wide field including all drop sizes in opposite to the validation, where droplets less than 10 $\mu$m were excluded. The other parameters are pesticide 4 g ha$^{-1}$ (400 $\mu$g m$^{-2}$), fluid 300 L ha$^{-1}$, boom height 0.5 m, sprayer speed 7 km h$^{-1}$, nozzle AI 110 04 at 0.3 MPa, wind speed 4 m s$^{-1}$ at 4 m, wind direction perpendicular to hedgerow, relative humidity 60%, air temperature 15°C, heat flux 100 W m$^{-2}$, and aerodynamic roughness 0.1 m. The considered pesticide had the following characteristics: vapor pressure 7.7 mPa (25°C), density 1.447 $10^3$ kg m$^{-3}$, and molar mass 381.37 g mol$^{-1}$.[28–30] Adapting values from other pesticides,[32,33] the binary diffusion coefficient in $N_2$ (25°C) was 5 $10^{-6}$ m$^2$ sec$^{-1}$, and evaporation heat enthalpy was 98,000 J/mol. Heat capacity 4200 J kg$^{-1}$ K$^{-1}$ was assumed to be equal to that of air.

The model calculations are presented as vertical profiles of the horizontal pesticide flux at the edge of the sprayed field, *i.e.*, at a possible hedgerow location. Results are also presented as the deposition drift to the ground as a function of the distance from the field edge, which is relevant for neighboring biotopes with a negligible vertical dimension.

Sensitivity calculations have been performed for spray-application parameters (nozzle type, spray pressure, and boom height), pesticide evaporation pressure, and meteorological conditions (wind speed, relative humidity, and air temperature).

### 3.1. *Nozzle type and spray pressure*

An important parameter is the droplet spectrum of the nozzle. In Fig. 6, the modeled drift is presented in two ways, as the vertical distributions of the airborne horizontal spray drift or horizontal flux at the edge of a field and as the deposition to the ground downwind of the field for three types of nozzles. As expected, the nozzle with the largest number of small droplets gives the highest horizontal drift and deposition. Deposition differs between the nozzles with a factor of 5–6, whereas the airborne drift values differ with a factor of about 10. The difference in factors is due to the fact that the spray cloud of the XR 110-02 nozzle contains a larger amount of small droplets that stay airborne and have a lower deposition velocity. At 10 m distance from the boom, the deposition ranges from 0.1 to 1.0% of the applied amount. A horizontal drift of 10 ng $cm^{-2}$ corresponds to 25% of the nominal application rate of 40 ng $cm^{-2}$. This number is extremely high compared to the ground deposits at 10 m distance, but as stated above the horizontal drift represents the cumulative dose from a 240-m wide field where most of the deposition to the ground occurs close to the sprayed track while the airborne horizontal drift moves over longer distances. The higher airborne drift values compared to deposition drift values are confirmed by Donkersley and Nuyttens.[32]

The sensitivity of drift to differences in nozzle pressure is mainly caused by the effect on the droplet size spectrum and only slightly by the increased initial droplet speed. The calculated difference of the drift for the nozzle Hardi 4110-16 at 0.3 and 0.55 MPa is only about 7% (not shown).

Compared to the range of ground depositions reported from the databases referenced by Teske *et al.*,[7] our calculated deposition is underestimated at the first 0–5 m, but the setups in the scenarios may differ. The reason for this possible underestimation may be that the initial deposition calculated with the sinking plume is assumed only to occur inside the sprayed track.

### 3.2. *Spray-boom height*

The effect of boom height is calculated (not shown). Doubling the boom height from 0.5 to 1 m increased the horizontal flux at the hedgerow by a factor of about 2.3. Halving the height to 0.25 m only reduced the values by about 15%. These results should be considered with some caution, because they have not been validated.

### 3.3. *Pesticide evaporation pressure*

The evaporation pressures of common pesticides are extremely low and vary by orders of magnitude up to about 30 to 46 mPa.[33,34] Compared to water (vapor pressure of about 10 hPa), the evaporation of pesticides is about $10^6$ times lower. Runs of the model with metsulfuron-methyl with an increased evaporation pressure (77 mPa instead of 7.7 mPa) did not affect the amount of spray drift.

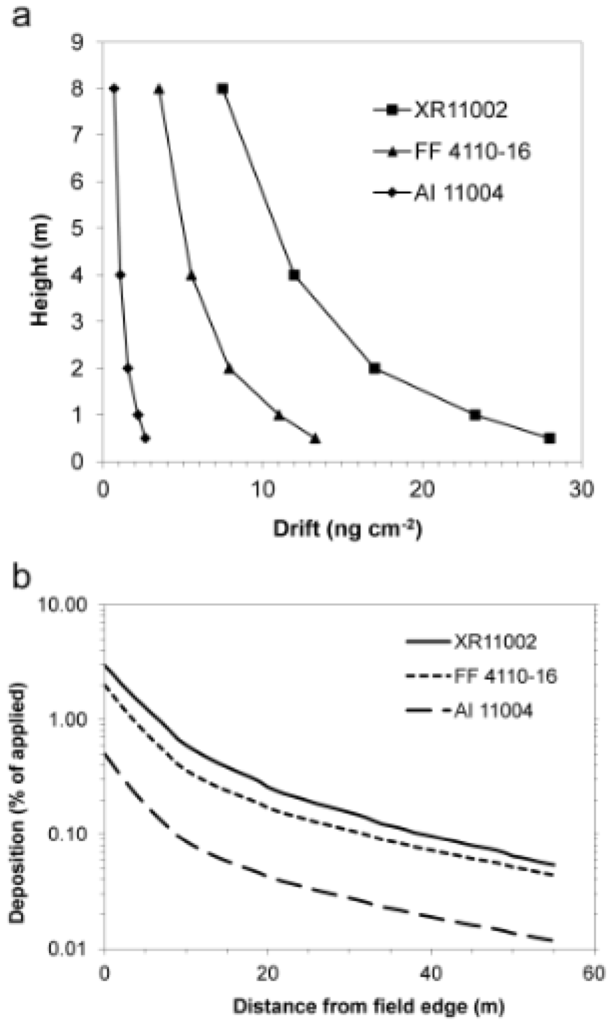

**Fig. 6.** Modeled vertical distributions of the airborne horizontal spray drift at the edge of a field (A) and deposition to the ground downwind of the field (B) for different types of nozzles: the standard flat-fans Hardi 4110-16 and XR 110-02 and the air-induction nozzle TeeJet AI 110-04. Values are the cumulated drift for a 240-m wide sprayed field. The value 10 ng $cm^{-2}$ corresponds to 25% of the applied pesticide of 400 $\mu g\,m^{-2}$. Other spray parameters and conditions are listed in the text.

### 3.4. *Wind speed, relative humidity, and air temperature*

Wind speed is the most important meteorological parameter. In Fig. 7, drift values are shown for wind speeds of 2, 4, and 6 m $sec^{-1}$. As expected, increasing wind speed increases horizontal drift. The relative humidity of the air also plays a role in the amount of drift. Calculations (not shown) with relative humidity decreasing from 100 to 40% result in a gradual drift increase of about 70%. For low humidity, the droplets evaporate faster, and the reduced diameter results in lower fall speeds that increase

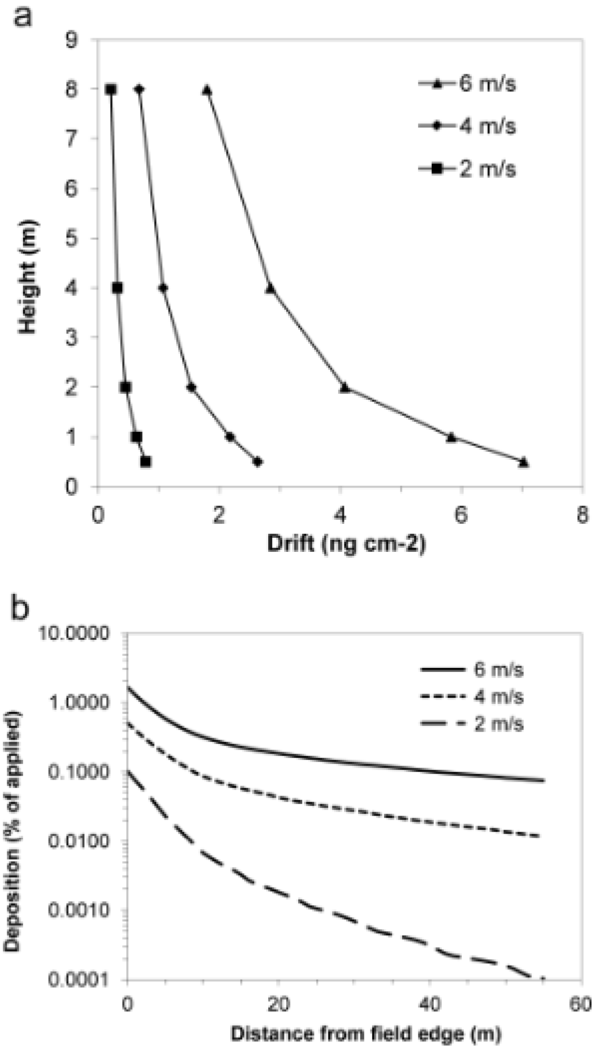

**Fig. 7.** Modeled spray drift at the edge of a field (A) and deposition to the ground downwind of the field (B) for different wind speeds. Other spray parameters and conditions are listed in the text.

the drift. Air temperature has the same effect on evaporation rate. Increasing temperature from 5 to 25°C increased drift by about 10–30% (not shown). Almost the same temperature dependence is calculated for the Hardi nozzle (not shown). The important effect of temperature and humidity on drift values corresponds with the results of Nuyttens *et al.*[1)]

*4. Limitations*

Although the model is based on reasonable physical principles, one should be cautious about changing the setup parameters too much, since only limited variations were available for calibration and evaluation. This concerns boom height, tractor speed, the minimum boom width of 12 m, and non-flat terrain. The effects of additives have not been addressed. The results will not be valid after the spray cloud has passed a possible hedgerow, as measured by De Schampheleire *et al.*[20)]

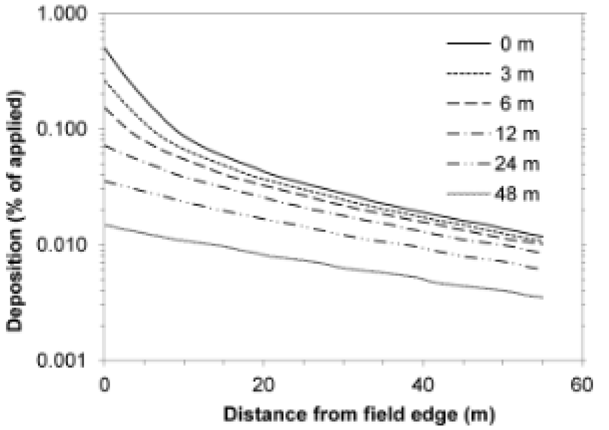

**Fig. 8.** Modeled spray deposition (% of field application) to the ground surface outside a 240-m wide field for different sizes of spray-free zones. The width of the zones is listed in the figure. Other spray parameters and conditions are listed in the text.

## Potential for Reduction of Exposures

The exposure of hedgerows and other neighboring biotopes to pesticides can be reduced by the introduction of spray-free buffer zones. The reduction of exposure depends on the width of the buffer zones, as demonstrated in Fig. 8, where deposition to the ground is calculated. The calculated values are the cumulative deposition from a 240-m wide field. The reduction of the deposition increases with increasing zone width. Compared to the standard situation without a buffer zone, the deposition at 40 m distance in biotopes with low vertical dimension is reduced by 33, 50, and 75% for buffer zone widths of 12 m, 24 m, and 48 m, respectively.

For the same situation, the exposure of a hedgerow is calculated in Fig. 9. The largest reduction occurs at the lowest levels as the width of the buffer zone increases. At the height of 8 m, the reduction is very limited. This is because it typically takes about 80 m before the airborne drift reaches a height of 8 m, and thus, the buffer zone of 48 m does not change the exposure at the top of a hedgerow. A maximum in the airborne drift profile appears just above the surface, which corresponds with our measurements. The same has been measured and modeled by Butler, Ellis and Miller[10)] and supports the use of deposition velocity methods that assume this gradient to exist.

Clearly, the meteorological parameters' influence on the amount of spray drift emphasizes the importance of spraying during, *e.g.*, the early morning hours, where speed and temperature are low and humidity is high. The type of nozzle, boom height, and pressure are, of course, also important.

## Conclusion

The OML-SprayDrift model is developed using two well-tested principles, the Gaussian tilting plume and the traditional Gaussian reflected plume, with deposition calculated from deposition velocities depending on droplet fall speed and air turbulence.

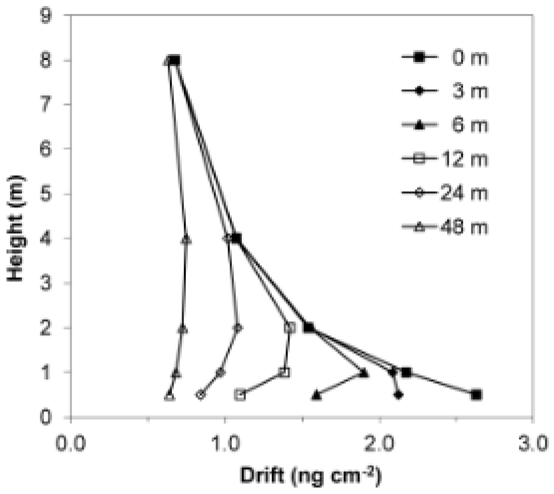

**Fig. 9.** Modeled vertical profile of the horizontal spray drift (ng m$^{-2}$) for different sizes of spray-free zones at the border of a 240-m wide field. The width of the zones is listed in the figure. The value 1 ng cm$^{-2}$ corresponds to 2.5% of the applied pesticide of 400 $\mu$g m$^{-2}$. Other spray parameters and conditions are listed in the text.

Model sensitivity to variation in meteorological and spray-application parameters behaves as expected from a physical point of view. The model's initial droplet fall distance is calibrated for a standard flat-fan nozzle, and model performance is validated against an air-injection nozzle with a completely different droplet size spectrum. In spite of this challenge, the validation still shows a high accuracy of the model, and this strengthens confidence in the model.

In the model, the initial adjustment of droplet fall distance is solely dependent on wind speed at boom height. Other models use a correction independent of wind speed but use parameterizations of airstream velocity close to the nozzle that is fitted to the different types of nozzles. The accuracy of the OML-SprayDrift model should be further improved by applying this type of principle.

For the OML-SprayDrift model validation against existing experimental data for a wider span of meteorology, boom heights, additives, and crop types would be desirable in order to integrate these parameters in a future version. In general, there is a need for more accurate field trial experiments with a higher resolution. Additionally, scale-wind tunnel experiments under controlled and repeatable conditions can mean a step forward in further model refinement.

## Acknowledgements

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## Bilag 3: The OML-SprayDrift supplemental

**Supplemental Materials 1:**

## Droplet evaporation and fall speed model

### *1. Mass*

The equation for mass of the droplet expresses the increase of mass is equal to the evaporation or condensation of water and solute (e.g. pesticide) on the surface:

$$\frac{dm}{dt} = \pi d^2 (G_w + G_s)$$

where $t$ [s] is the time, $m$ [kg] is the mass of the droplet, $d$ [m] is the diameter of the droplet and $G_w$ and $G_s$ [kg m$^{-2}$ s$^{-1}$] is the flux of water and solute, respectively, at the surface of the droplet, defined positive towards the drop.

The flux of water vapour by diffusion between the surface of the drop and the surrounding air is given by:

$$G_w = \frac{Sh_{H2O}\, D_{H20}}{d} \frac{M_{H2O}}{R\, T_f} (p_{H2O,a} - x_w\, p_{H2O,f})$$

and the flux of solvent vapour by:

$$G_s = \frac{Sh_s\, D_s}{d} \frac{M_s}{R\, T_f} (p_{s,a} - (1 - x_w) p_{s,f})$$

where subscripts *H2O* and *s* refer to water and solvent, respectively. *Sh* is the Sherwood number and *D* is the diffusion coefficient of vapour in nitrogen (air) which is calculated at the droplet film temperature $T_f$ [K]. $M_{H2O}$ is the molecular weight of water, *R* is the universal gas constant, $p_{*,a}$ vapour pressure in the air and $p_{*,f}$ saturation vapour pressure at the surface of the drop. The film temperature is defined as the mean of the air temperature and the temperature at the surface of the droplet. The water vapour pressure is modified by the presence of the solvent and vice versa. According to Seinfeld and Pandis$^{1)}$, the water vapour pressure is modified by the molar fraction of water in the solution, $x_w$ for substances totally dissolved in water:

$$x_w = \frac{n_w}{n_w + n_s}$$

where $n_w$ is the number of mole of water and $n_s$ is the number of mole of the solvent.

A combination of the equations gives:

$$\frac{d(d^2)}{dt} = \frac{4}{\rho\, R\, T_f}(M_{H2O}\ D_{H2O}\ Sh_{H2O}(p_{H2O,a} - x_w p_{H2O,f}) + M_s\ D_s\ Sh_s(-(1-x_w)p_{s,f}))$$

assuming no solvent in the ambient air and where $\rho$ is the density of the droplet calculated as:

$$\rho = (1 - vol_s)\rho_{H2O} + vol_s \rho_s$$

where $vol_s$ is the volume of the solute $m_s\, \rho_s^{-1}$.

The vapour pressure at the surface of the drop is taken as the saturated pressure at the temperature of the surface of the drop. The only parameter needed to be modelled is the Sherwood number. Bird et al.$^{2)}$ express the Sherwood number as:

$$Sh_* = 2.0 + 0.6\ Re^{1/2} Sc_*^{\ 1/3}$$

where the Reynolds number, $Re$ and the Schmidt number, $Sc$ of the droplet is defined as:

$$Re = \frac{d\, v \rho_a}{\mu_a}$$

$$Sc_* = \frac{\mu_a}{\rho_a D_*}$$

where $v$ is the velocity of the drop relative to the air, $\rho_a$ is the density of the air, $\mu_a$ is the dynamic viscosity of air and * refers to either water or solvent.

### 2. *Momentum*

The equation of momentum for a droplet expresses that the increase in momentum is the sum of the acting forces, i.e. the force due to gravity and the force at the surface due to the friction at the surface:

$$m\frac{dv}{dt} = mg - 3\,\pi\, d\,\mu_a v\, f$$

where $g$ is gravity and $f$ is a factor, that describes the deviation from the Stokes (creeping) flow. According to Boothroyd[3), $f$ is modelled as follows:

$$f = 1.0 + 0.15\, Re^{0.687}$$

with

$$\tau_m = \frac{\rho\, d^2}{18\,\mu_a\, f}$$

The momentum equation is transformed to:

$$\frac{dv}{dt} = g - \frac{v}{\tau_m}$$

which, for a constant $\tau_m$ through the integrating time step, gives:

$$v = \exp\left(\frac{-t}{\tau_m}\right) v_0 + \left(1 - \exp\left(\frac{-t}{\tau_m}\right)\right) g\,\tau_m$$

where $v_0$ is the velocity of the drop at the beginning of the time step $t = 0$.

### 3. *Energy*

The energy equation of the droplet expresses that the increase of the thermal energy of the drop is equal to the enthalpy from condensing vapour and the energy exchange with the air due to conduction and convection:

$$(m_{H2O}\, Cp_{H2O} + m_s Cp_s)\frac{dT}{dt} = \frac{dm_{H2O}}{dt} h_{evap,H2O} + \frac{dm_s}{dt} h_{evap,s} + \pi\, d^2 \frac{Nu\, k}{d}(T_a - T_s)$$

where $Cp_*$ is the heat capacity of water and solute, $T$ is the temperature of the drop, $T_a$ is the air temperature, and $h_{evap*}$ is the enthalpy of evaporation at the surface temperature of the drop *Ts*. *k* is the heat conduction coefficient of the air and *Nu* is the Nusselt number at film temperature. The Nusselt number is modelled according to Boothroyd3) and Bird et al.2) as:

$$Nu = 2.0 + 0.6\,Re^{1/2}\,Pr^{1/3}$$

where the Prandtl number is defined as:

$$\Pr = \frac{\mu_a\, Cp_a}{k}$$

With

$$\tau_e = \frac{d^2 \rho}{6\,Nu\,k}\left( \frac{G_{H2O}}{G_{H2O} + G_s} Cp_{H2O} + \frac{G_s}{G_{H2O} + G_s} Cp_s \right)$$

and the assumption, that the surface temperature of the drop is equal to the temperature of the drop, the energy equation can be rewritten as:

$$\frac{dT}{dt} = \frac{h_{evap}^{'}}{Cp^{'}} \frac{3}{d} \frac{d\,d}{dt} + \frac{T_a - T}{\tau_e} \quad with \quad \frac{h_{evap}^{'}}{Cp^{'}} = \frac{h_{evap,H2O} G_{H2O} + h_{evap,s} G_s}{Cp_{H2O} G_{H2O} + Cp_s G_s}$$

This is integrated in the same manner as the moment equation:

$$T = \exp\left(\frac{-t}{\tau_e}\right) T_0 + \left(1 - \exp\left(\frac{-t}{\tau_e}\right)\right)\left(\frac{h_{evap}^{'}}{Cp^{'}} \frac{3}{2} \frac{d(\ln(d^2))}{dt} \tau_e + T_a\right)$$

where $T_0$ is the temperature of the drop at the beginning of the time step, $t = 0$. The minor changes in the values of *Cp, k,* $\rho$*, μ, D,* $h_{evap}$*,* and *p* due to temperature are taken from textbooks.

### Evaluation of the droplet model

The drop model has been evaluated against two different series of measurements on pure water. In Table S.1, the predicted fall velocities are compared with velocities measured by Gunn and Kinzer4,5). The model is set up with a relative humidity of 100 % in order to avoid evaporation; a start velocity of 0 m/s and run until at constant terminal velocity is reached. The droplet velocities correspond very well with measurements, particular for droplets less then 400 µm where the most important spray drift occurs.

[Table S.1]

The model capability to predict evaporation has been evaluated by comparing the drop size after 0.5 m of fall distance with calculations from another model, Fluent®[6)] that has been evaluated against experiments for 148, 253 and 424 µm droplets in about 40 % relative humidity[7)]. In Table S.2, the comparison is performed for droplets with a start velocity of 20 m/s and relative humidities of 20, 40, 60, and 80%. Generally, the model predicts smaller droplets than Fluent®. The reason for the larger diameter calculated by Fluent® is probably that Fluent® was run with a fixed droplet evaporation temperature of 0° C which is too low and, in some cases, lower than the wet bulb temperatures of 9, 12, 15, and 18° C for the respective relative humidities. In our model, the evaporation temperature was calculated during evaporation and was close to the wet bulb temperatures. The lower evaporation temperature in the Fluent® runs gives lower evaporation and, in turn, a larger diameter.

[Table S.2]

## References

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Table S.1

Evaluation of droplet terminal speed (m/s).

| Droplet diameter (µm) | Measurement | Model |
|---|---|---|
| 100 | 0.27 | 0.25 |
| 200 | 0.72 | 0.71 |
| 300 | 1.17 | 1.17 |
| 400 | 1.62 | 1.61 |
| 500 | 2.06 | 2.03 |
| 600 | 2.47 | 2.42 |
| 700 | 2.87 | 2.80 |
| 800 | 3.27 | 3.16 |

Table S.2

Droplet diameter (µm) after 0.5 m fall distance and start velocity of 20 m $s^{-1}$ for different relative humidity (Rh.) and air temperature 20° C. Comparison with the model of Reichard et al.[6)].

| Start droplet diameter (µm) | Rh. 20% | | Rh. 40% | | Rh. 60% | | Rh. 80% | |
|---|---|---|---|---|---|---|---|---|
| | Reichard | Model | Reichard | Model | Reichard | Model | Reichard | Model |
| 60 | 0* | 0* | 0* | 0* | 39 | 0* | 53 | 47 |
| 80 | 62 | 45 | 68 | 61 | 73 | 70 | 77 | 75 |
| 100 | 92 | 88 | 94 | 92 | 97 | 95 | 98 | 98 |
| 200 | 200 | 199 | 200 | 199 | 200 | 199 | 200 | 200 |

* Droplet is completely evaporated

## Generalisering og validering af model for afdrift af pesticider til læhegn og andre marknære biotoper

I det netop afsluttede projekt "Generalisering og validering af model for sprøjtemiddelafdrift til læhegn og andre marknære biotoper" har vi målt, hvor meget af det sprøjtemiddel, landmanden sprøjter ud, der ender i markens læhegn. Målingerne er anvendt til at videreudvikle og validere en model, der kan forudsige afdriften af de fleste sprøjtemidler under forskellige betingelser. Modellen kan tage hensyn til de givne egenskaber for pesticidet og til dysens dråbestørrelser, hvordan vejret er og om der er en sprøjtefri zone mellem traktoren og naturen uden for marken. Desuden kan modellen differentiere mellem forskellige højder i læhegn.  Som forventet var afdriften til læhegn mindre ved brug af en luftinjektions-dyse end ved sprøjtning med fladsprede-dyse i den samme mark. Forskellen i afdrift mellem de to typer af dyser viser, at der er potentiale for, via valg af sprøjteudstyr, at reducere mængden af pesticider, der lander i læhegnene og dermed reducerer blomstring og frugtsætning. Samtidig viser såvel målinger som modelberegninger, at der ikke er den store effekt af sprøjtefrie bufferzoner på afdriften til læhegn, specielt ikke i den øverste del af læhegnene, hvor frugterne ofte er mest talrige.

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