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Smoke puffs as models for the study of spore dispersal in and above a cereal crop

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Turbulent transfer has been cited as the mechanism by which rust spores ascend from the three-dimensional crop volume where they are formed through the "outer active surface" of the crop into the "turbulent boundary layer". There are several highly sophisticated accounts of the diffusion of air-borne particles, including fungus spores. These employ mathematical equations that are beyond the understanding of most plant pathologists (see Gregory, 1961). Oort (1940) demonstrated an aspect of turbulent spore dispersal using a plant pathogen. Smoke puffs can be used to demonstrate the movement of air parcels through the "outer active surface" of the crop.

An experiment was conducted at Wageningen in a field of barley cv. 'Topper' on July 20, 1964, at ca 3 h 00 p.m. The crop was thin (60 stems/m^2) and nearly ripe. The "outer active surface", taken to be the plane connecting the tops of the ears, was at 70 cm above soil surface. At 150 cm height the screen temperature was ca. 23 °C, relative humidity ca. 51 %, and air movement ca. 120 cm. sec^{-1}. The wind was light and with a tendency to blow from SE, cloudiness was 8, global radiation ca. 30 cal. cm^{-2}. $hour^{-1}$, 58 sunshine minutes from 2 to 4 p.m., precipitation nil.

Isothermic smoke puffs with an initial volume of ca. 60 ml were produced at various heights by means of a simple smoke generator (Auer Co, Berlin, No 5019). An 8 mm film camera with wide-angle lens was placed in a fixed position with the lens axis approximately perpendicular to the average wind direction. A panchromatic film was used at a speed of 16 exposures per second. Every fourth picture (time interval 0.25 seconds) was projected on transparent paper in order to draw the visible outline of the smoke puff.

The three-dimensional process is represented in a two-dimensional plane. Distant smoke clouds are represented as undersized puffs and puffs nearby the camera (see Fig. 9) appear on the screen as oversized clouds. For these reasons the absolute dimensions of the cloud drawings are meaningless; only the general behaviour of the smoke puffs and the changes in form are meaningful. The smoke puffs show movements of air parcels at two scales of dimension. At the smaller scale the movements extend the smoke clouds (Fig. 1 to 10). At the larger scale the movements displace the smoke puff as a whole; this movement is represented by the displacement of the centre of gravity of the smoke clouds (Fig. 11).

Eight out of 10 puffs moved upward, two downward. Five puffs moved in the general direction of the wind, the five others against the wind. The downward moving

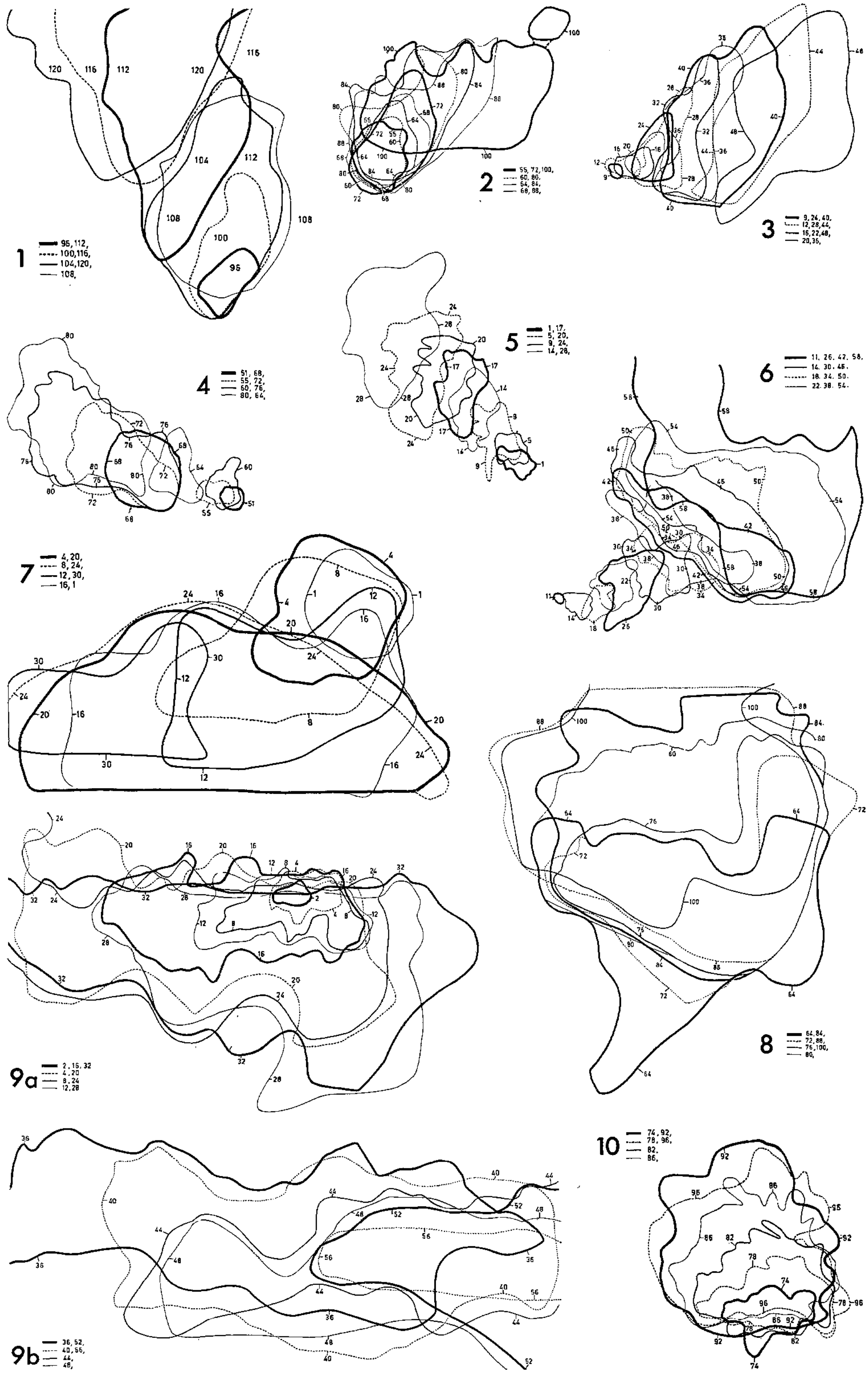
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Fig. 1–10. Development of single smoke puffs as demonstrated by their visible outlines drawn at successive 0.25 sec. intervals. The numbers accompanying the outlines refer to the corresponding exposure numbers on the film. The first outline of a puff was drawn as soon as possible after the appearance of the puff; its exposure number is not necessarily 1. Note the changes in the form of the smoke puffs and the variations in their displacement.

Fig. 1–10. De ontwikkeling van individuele rookwolkjes, weergegeven door hun zichtbare omtrek te tekenen met intervallen van 0,25 sec. De getallen bij de omtreklijnen corresponderen met beeldnummers op de film. De eerste omtreklijn van een rookwolkje werd zo spoedig mogelijk na het verschijnen van het wolkje afgetekend; het getal van een eerste omtreklijn is niet noodzakelijkerwijs 1. Let op de veranderingen in de vorm van de rookwolkjes en de variaties in hun verplaatsing.

Fig. 11. Displacement of smoke clouds in the plane perpendicular to the axis of the camera lens. For each of the smoke clouds numbered 1 through 10 the position of the centre of gravity of the cloud is given at the successive 0.25 sec intervals. The origin of the coordinates represents the position of the smoke puffs immediately after emission from the smoke generator. The X and Y scales are in arbitrary units of length; the value of a scale unit varies from puff to puff. Air parcels loaden with spores are supposed to show a behaviour similar to that of the smoke clouds.

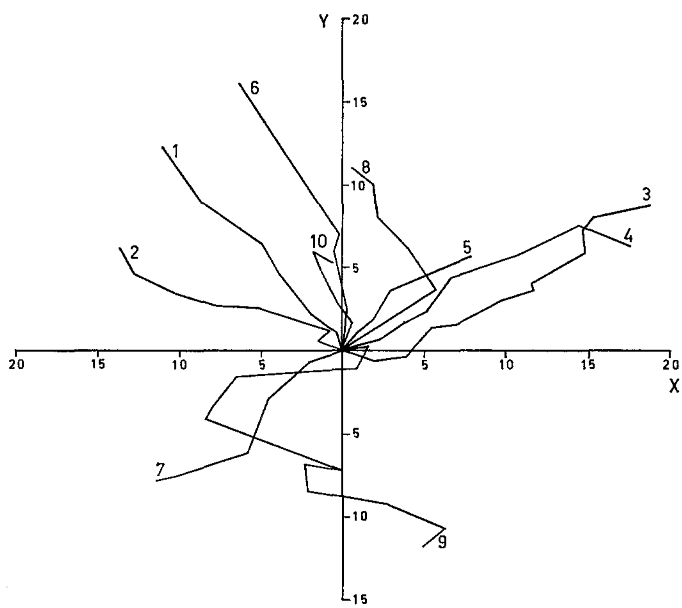

Fig. 11. Verplaatsing van rookwolkjes in het vlak loodrecht op de as van de cameralens. Voor ieder van de tien rookwolkjes is de plaats van het zwaartepunt van de wolk aangegeven met intervallen van 0.25 sec. De oorsprong van de coördinaten geeft de plaats van de wolkjes aan onmiddellijk nadat ze uit de rookgenerator zijn geblazen. De X en Y schalen zijn uitgedrukt in willekeurige lengte-eenheden, waarvan de waarde varieert van wolkje tot wolkje. Met sporen beladen luchtpakketjes vertonen vermoedelijk een gedrag gelijkend op dat van de rookwolkjes.

puffs 7 and 9 extended horizontally. After liberation of clouds their outline could be clearly observed from 28 to 60 sec. The centre of gravity of the cloud area had a maximum speed of 17 cm. sec^{-1} in the horizontal and 9 cm. sec^{-1} in the vertical direction. Radial extension of the visible edge of the clouds had a maximum speed of ca. 4 cm. sec^{-1}.

This case study was part of an investigation into the physical factors affecting the epidemiology of yellow rust, *Puccinia striiformis* Westend. In general, the bulk of uredospores is in the air above the crop around noon (Hirst, 1953) when convective turbulence is intense. Zadoks (1957) found the highest amount of uredospores of yellow rust in the air around 10 a.m. on a bright day. After take-off from the leaves the uredospores, according to current opinion, are dispersed through the crop volume and into the turbulent boundary layer by air movements as illustrated here.

Samenvatting

Rookwolkjes als modellen voor de studie van de verspreiding van sporen in en boven een graangewas

De verspreiding van roestsporen door turbulente luchtbewegingen wordt geïllustreerd met behulp van rookwolkjes. Rookwolkjes werden geproduceerd nabij het "actieve buitenoppervlak" van een gerstgewas. De bewegingen van de rookwolkjes werden gefilmd. Iedere kwart seconde werd de op de film zichtbare buitenomtrek van een rookwolkje op een tekening vastgelegd (Fig. 1 t/m 10). De verplaatsing van het zwaartepunt van ieder rookwolkje kon een aantal seconden gevolgd worden (Fig. 11). De waarnemingen ondersteunen de gangbare opvattingen over de verspreiding van uredosporen binnen de gewasruimte en vanuit het gewas naar de turbulente lucht daarboven.

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