Supplementary Information for: 'Sneezing' plants: pathogen transport via jumping-droplet condensation

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1 Model for Jumping with Spores

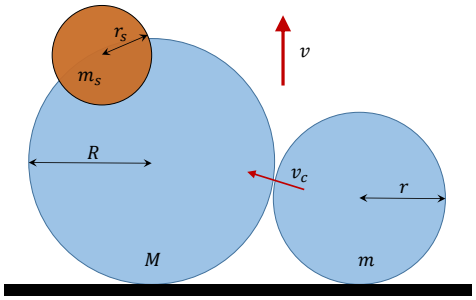

Figure S1: Schematic of two dew droplets merging, where a spore is adhering to the larger droplet.

We draw from the argument of Mouterde *et al.* [1] in order to derive the velocity of coalescence-induced jumping of dew droplets with spores. Consider two droplets, the larger one having a radius R and the smaller one has a radius r. Let n spores of radius r_s adhere to the larger droplet (Fig. S1). The degree of asymmetry is given by $\epsilon = r/R$. Let R_f be the post-merged radius of the jumping droplet, including the spores.

By conservation of mass, it follows that:

$$R_f^3 = R^3 + r^3 + nr_s^3. \tag{S1}$$

This equation can be re-written in terms of ϵ as:

$$\frac{R_f^3}{R^3} = 1 + \epsilon^3 + \frac{nr_s^3}{R^3}. \tag{S2}$$

The capillary-inertial velocity with which the smaller droplet merges with the larger one is $v_c \sim r/\tau_c$, where τ_c is the time scale that can be obtained by equating the capillary force γr with inertia $\rho r^2 v_c^2 \sim \rho r^4/\tau_c^2$:

$$\tau_c = 2\sqrt{\frac{\rho r^3}{\gamma}}. \tag{S3}$$

The pre-factor of 2 was found experimentally in[1]. Therefore $v_c = 1/2(\gamma/\rho r)^{1/2}$. Conservation of momentum dictates:

$$(M + m + m_s)v_s = mv_c. \tag{S4}$$

Plugging in for the masses and v_c we get:

$$\begin{aligned}
v_s &= \frac{1}{2}\sqrt{\frac{\gamma}{\rho R}}\,\frac{\epsilon^{5/2}}{1+\epsilon^3+nr_s^3/R^3} \\
&= \frac{1}{2}\sqrt{\frac{\gamma}{\rho R}}\,\epsilon^{5/2}\,\frac{R^3}{R_f^3} \\
&= \frac{1}{2}\sqrt{\frac{\gamma}{\rho R_f}}\,\epsilon^{5/2}\left(\frac{R}{R_f}\right)^{5/2} \\
&= \frac{1}{2}\sqrt{\frac{\gamma}{\rho R_f}}\,\epsilon^{5/2}\,\frac{1}{R_f^{5/2}}\left[\frac{R_f^3-nr_s^3}{1+\epsilon^3}\right]^{5/6} \\
&= \frac{1}{2}\sqrt{\frac{\gamma}{\rho R_f}}\,\frac{\epsilon^{5/2}}{(1+\epsilon^3)^{5/6}}\left(1-\frac{nr_s^3}{R_f^3}\right)^{5/6} \\
&= \left(1-\frac{nr_s^3}{R_f^3}\right)^{5/6} v.
\end{aligned} \tag{S5}$$

2 Spore-Counting Experiments

Protocol and Design: Three wheat leaves were selected from three-month-old plants, inoculated eight days prior to the experiments. Each diseased leaf was divided into a top, middle, and bottom section as shown in Fig. S2a. We conducted spore-counting experiments only with the middle part, as it was visibly more sporulated than the top and the bottom. The middle section was then further divided into three sections: upper, central and lower.

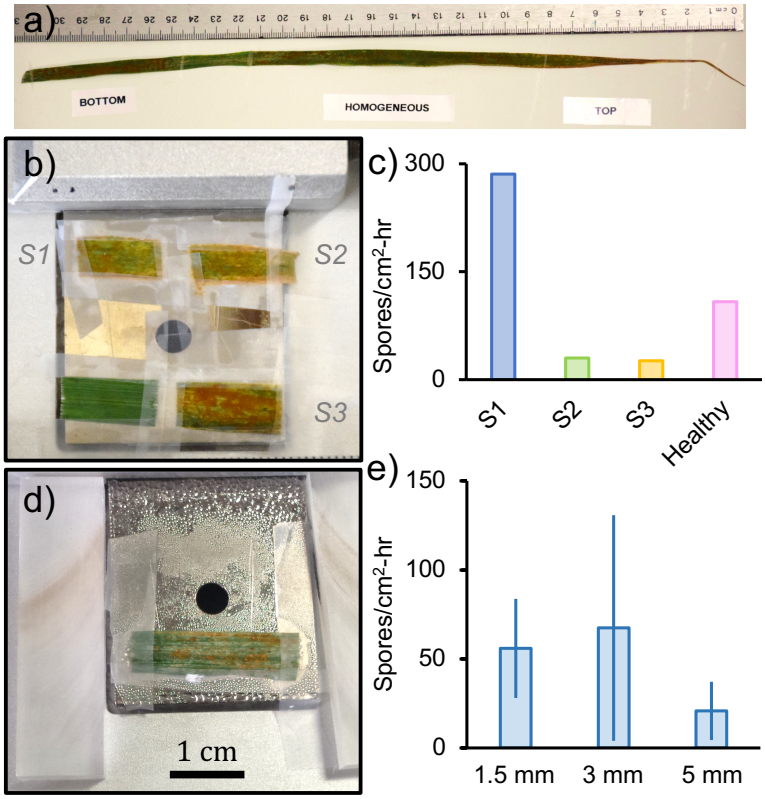

Figure S2: Spore-Counting Experiments: a) A typical sporulated wheat leaf and its divisions. The middle section was usually the more homogenous and densely sporulated section. b) Preliminary setup with 4 wheat leaves: 3 diseased and 1 healthy, all put together on a Peltier Stage with a water-sensitive paper at a height of 1.5 mm above the leaf. c) Evidence of cross-talk: spores were collected even over the healthy leaf. d) Final setup comprising only one leaf. e) Number of spores liberated from the leaf surface in 1 hr as collected at a height 1.5 mm, 3 mm and 5 mm respectively.

In our preliminary experimental design, four leaf pieces were simultaneously bonded to the Peltier stage, each piece being a 1 cm × 3 cm portion. Three of these pieces were from three different diseased leaves while one was a control from a healthy leaf. The cut pieces were thermally bonded to a Peltier stage (Fig. S2b) and the absorbent paper was held above the Peliter using the acrylic spacers as described in Materials and Methods. The motive for placing four different leaves all together on the Peltier stage was to directly compare their spore liberation rates under absolutely identical conditions. However, as seen in Fig. S2c, spores were collected even for the water-sensitive paper lying over the healthy leaf which had no spores. Even when we tried the same experiment with only

one sporulated leaf and one healthy leaf, spores were still observed to collect on the paper above the healthy leaf. As a control test, a healthy leaf was placed in isolation on the Peltier stage and no spores were found on the paper as expected. This means that the spores over the healthy leaf in the other cases were due to oblique jumping trajectories from the diseased leaves.

Therefore only one leaf section should be tested at a time, otherwise it is impossible to know which spore came from which leaf section. The final set-up thus comprises only a single leaf on the Peltier stage (Fig. S2d). Experiments were done for heights of 1.5 mm, 3 mm and 5 mm respectively. Fig. S2e shows the average number of spores collected from 1 hr at different heights from the leaf surface.

Spore Counting and Clustering Protocol: The water-sensitive Sygenta paper is unique in its property of changing color from yellow to blue when water touches it. However, spores collected on the paper sometimes showed a blue splash pattern, and sometimes did not. This was because micrometric droplets that carry spores were not always large enough to cause the paper to change color. Furthermore, the process of raster-scanning and counting often took hours, and in that time the paper could possibly lose moisture and consequently lose some color too. Therefore we focused more on the quantification of the spores, which were easy to identify, as opposed to the droplets carrying the spores.

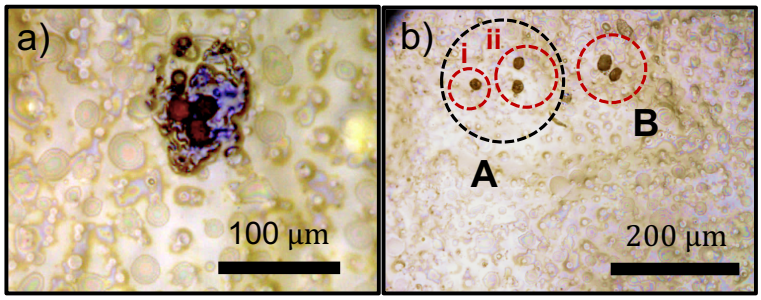

Figure S3: Spore-Counting Experiments: (a) Experimental micrograph of three sporse collected on the water-sensitive paper with a splash pattern. (b) Spores collected on the paper without a splash pattern. Red circles indicate clusters separated by one-spore distance or less.

To estimate how many spores were adhering to a single jumping droplet that reached the paper, the following protocol was followed:

1) When a blue pattern was visible (Fig. S3a), all spores within the blue region were considered to be within a single droplet. It is of course possible that a second droplet (with or without spore) had jumped onto the same spot, thus giving a false impression of more spores per jumping droplet than really existed. However, the density of droplets and spores on the paper was moderate enough that such cases can be considered rare and neglected for the purposes of estimating spore clusters per droplet.

2) For smaller jumping droplets, the blue pattern was not always visible on the paper. In this case, we assume that spores on the paper were from the same droplet if the edge-to-edge distance between any two spores is less than the size of the spore diameter ($\approx 20\,\mu$m). An illustration of this method is shown in Fig. S3b). In this figure, A is not considered as a cluster, but B is. This is because unlike B, A has sub-units i and ii which are separated by more than 1 spore distance.

3 Vibration Experiments: Vertical Dislodging of Dry Spores

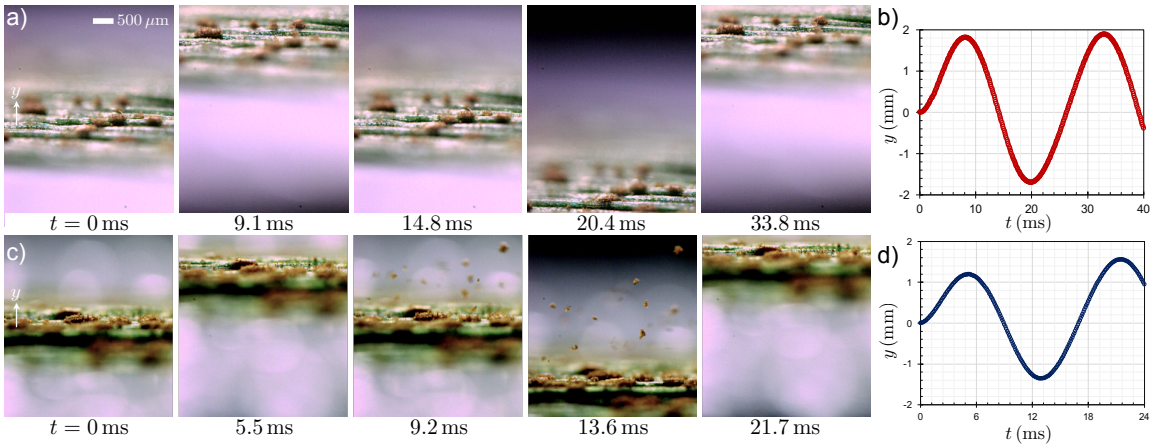

Figure S 4: Expanded version of Fig. 6a,b from the main text. A 5 cm length segment was cut from a typical sporulated wheat leaf and directly taped to a mechanical wave driver (PASCO, SF-9324). The amplitude and frequency of the driver were controlled using a function generator (Agilent, 33210A) along with a power amplifier (KROHN-HITE, 7500). The resulting vibration was captured using a side-video high-speed camera. (a,b) No spores were removed from the leaf when the frequency was set to 40 Hz with a peak-to-peak amplitude of 3.6 mm. (c,d) In contrast, some of the spores were detached from the leaf when the frequency was set to 60 Hz with a peak-to-peak amplitude of about 3 mm, which corresponds to a maximum velocity of $v_v \approx 0.6$ m/s.

The following scaling analysis can roughly estimate the wind velocity required to generate the critical vibration necessary for spore liberation. The acceleration imparted by the vibration stage is $4\pi^2 f^2 A$, where f is the frequency and A is the amplitude. For the best-case scenario of the wind attacking the leaf perpendicularly, the wind imparts a force $F_\mathrm{w} \sim (1/2)\rho_\mathrm{a} U^2 A_\mathrm{l}$, where A_l is the leaf area. This force is equated to $\rho_\mathrm{l} A_\mathrm{l} t 4\pi^2 f_\mathrm{c}^2 A_\mathrm{c}$, where $t \sim 10^{-4}$ m is the typical thickness of the wheat leaf and the critical vibrational acceleration was achieved at $f_\mathrm{c} = 60$ Hz and $A_\mathrm{c} = 1.5$ mm (Fig. S4c,d). A sporulated leaf has a density close to water, $\rho_\mathrm{l} \sim 10^3$ kg/m^3. This gives a critical wind speed of $U_\mathrm{c} \sim (8\pi^2 f_\mathrm{c}^2 A_\mathrm{c} t \rho_\mathrm{l}/\rho_\mathrm{a})^{1/2}$. Plugging in all values, we obtain $U_\mathrm{c} \sim 1$ m/s.

4 Wind Tunnel Experiments: Shearing off Dry Spores

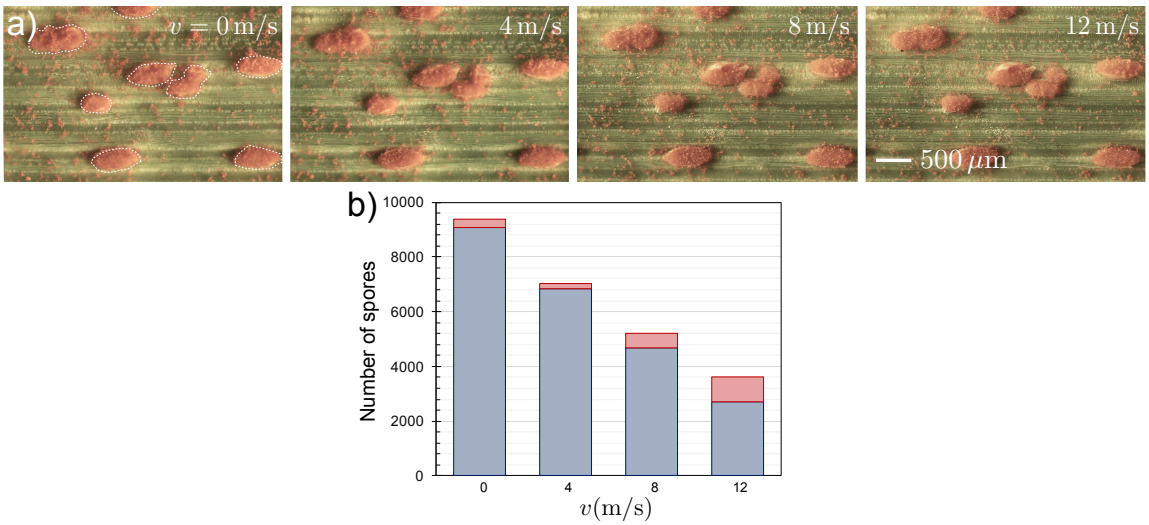

Figure S 5: (a) Experimental results of a sporulated wheat leaf under air flow with different velocity. Top-down microscopy was used to compare the initial spore distribution (first frame) to that after being subjected to 4, 8, or 12 m/s winds (frames 2–4). (b) A histogram comparing the total number of isolated spores (red) and spores contained within agglomerates (blue) before and after being subjected to the various wind speeds. The pustules were not counted, only spores residing on the actual leaf surface. The number of spores contained within agglomerates was estimated by measuring the total projected surface area of an agglomerate and dividing by the 10 μm spore diameter, assuming that most clusters only contained about one layer of spores. These measurements reveal that while gusts of wind are effective at removing the larger spore clusters, they are ineffective at removing isolated spores. Indeed, the number of isolated spores on the surface actually increases with wind speed, which is likely due to a subset of spores within a sheared cluster remaining on the surface during liberation.

5 Video Captions

Compilation of selected videos of coalescence-induced jumping of dew droplets on healthy as well as diseased wheat leaves. The videos include isometric, sideview as well as topdown imaging. Typically, the surface of the wheat leaf was held at 0 °C, while the air temperature $T_\infty = 24 \pm 4$ °C and humidity was $H = 60 \pm 11\%$.

References

[1] T. Mouterde, T. V. Nguyen, H. Takahashi, C. Clanet Christophe, I. Shimoyama, and D. Quéré. How merging droplets jump off a superhydrophobic surface: Measurements and model. *Phys. Rev. Fluids*, 2:112001, 2017.