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ORIGINAL PAPER

Small fluctuations in the recovery of fusaria across consecutive sampling intervals with unmanned aircraft 100 m above ground level

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Abstract The aerobiology of fungi in the genus *Fusarium* is poorly understood. Recent work has highlighted the role of Lagrangian coherent structures (LCSs) in the movement of fusaria in the lower atmosphere. Here, we extend this work by examining the relationship between the length of atmospheric sampling intervals with autonomous unmanned aerial vehicles (UAVs) and the recovery of fusaria. UAVs were equipped with an array of eight microbe-sampling devices with four "inner" sampling arms and four "outer" sampling arms. Each set of arms was used to collect consecutive aerobiological samples during 10 min sampling periods at 100 m above ground level at the Kentland Farm in Blacksburg, Virginia. Fifty-one flights (102 consecutive sampling intervals) were conducted in 2010 and 2011. A correlation analysis showed that the counts of fusaria did not vary between the inner and outer sampling arms from consecutive sampling period of 10 min ($r = 0.93$, $P < 0.001$), and the frequency of colony counts had similar distributions for samples from the inner and outer sampling arms. An analysis of the temporal variation in the collections of *Fusarium* showed that the similarity between collections decreased over time. This work supports the idea that atmospheric populations of fusaria are well mixed, and large changes in the recovery of fusaria in the lower atmosphere may be attributed to large-scale phenomena (e.g., LCSs) operating across varying temporal and spatial scales. This work may contribute to effective control measures for diseases causes by fusaria in the future.

Keywords Fungi · Aerobiological sampling · Pathogen · Unmanned aerial vehicles · UAV · Lagrangian coherent structure · Long-distance transport · Atmospheric transport barrier · Selective medium

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1 Introduction

Fusarium is one of the most important genera of fungi on Earth (Leslie and Summerell 2006). Members of this genus cause a number of devastating plant diseases and can threaten the health of both domestic animals and humans through the production of mycotoxins (Berek et al. 2001; McMullen et al. 1997). Many fusaria are transported through the atmosphere from one habitat to another (Schmale et al. 2012; Tallapragada et al. 2011). Previous work has shown that large-scale atmospheric features known as Lagrangian coherent structures (LCSs) or atmospheric

transport barriers (ATBs) are associated with the long-distance transport of *Fusarium* in the lower atmosphere (Schmale et al. 2012; Tallapragada et al. 2011). ATBs are moving boundaries that effectively separate air masses of qualitatively different dynamics and may play a significant role in the movement of microbes among habitats (Lekien and Ross 2010; Senatore and Ross 2011). Tallapragada et al. (2011) showed that LCSs (ATBs) were associated with changes in atmospheric counts of *Fusarium*. Though the work by Tallapragada et al. (2011) was the first to demonstrate that large fluctuations in atmospheric counts of *Fusarium* could be attributed to the passage of ATBs, it was unable to account for small-timescale fluctuations that might explain natural fluctuations among the collections of *Fusarium.*

Recently, members of our research team have developed technologies with autonomous unmanned aerial vehicles (UAVs) to track the movement and structure of populations of microbes such as *Fusarium* in the lower atmosphere (Schmale et al. 2008). The UAVs were equipped with microbe-sampling devices that contained a total of four Petri plates that were opened and closed by remote control from the ground once the UAV was aloft (Schmale et al. 2008). In the present study, we used a new array of sampling devices that contained a total of eight Petri plates, with four "inner" sampling arms and four "outer" sampling arms that were used to collect consecutive aerobiological samples during 10 min sampling periods at 100 m above ground level. This method was used to test the null hypothesis that the recovery of fusaria would not vary across consecutive (a 10-min sample on the inner arms, immediately followed by a separate 10-min sample on the outer arms) aerobiological sampling intervals with UAVs 100 m above ground level. Thus, large fluctuations in the recovery of fusaria could be attributed to a suite of factors including the passage of LCSs (ATBs) and/or the contribution of local sources, and not random fluctuations in counts of *Fusarium* that would be the representative of a "natural" condition. The specific objective of this study was to determine whether the collections of fusaria vary between the inner and outer sampling arms of a UAV from consecutive sampling period of 10 min. This work is prerequisite for understanding whether changes in the recovery of fusaria in the lower atmosphere may be attributed to large-scale phenomena (e.g., LCSs) operating across varying temporal and spatial scales and may contribute to effective control measures for diseases causes by fusaria in the future.

2 Materials and methods

2.1 Autonomous unmanned aerial vehicles (UAVs) for sampling

Autonomous (self-controlling) UAVs were used to collect *Fusarium* from the atmosphere above Virginia Tech's Kentland Farm in Blacksburg, VA, USA. The UAVs consisted of a Sig Rascal© airframe equipped with an autopilot computer and a suite of onboard telemetry devices (Schmale et al. 2008) and were programmed to fly a circular sampling pattern at a target altitude of 100 m above ground level and a nearly constant speed of 90 km/h. Each UAV carried eight collection plates containing a *Fusarium* selective medium on the wings. The eight sampling plates were separated into "inner" and "outer" sampling arms (Fig. 1). For consecutive sampling flights, a 10-min sample was collected using the inner arms (4 plates were exposed during this sampling interval), immediately followed by a separate 10-min sample using the outer arms (4 plates exposed were exposed during this sampling interval) (Fig. 1). Sampling flights were also conducted with the inner and outer sampling devices open at the same time (8 plates exposed during the sampling interval).

2.2 Culturing and identification of *Fusarium*

A Fusarium selective medium (FSM) (Schmale et al. 2006) was used to bias our atmospheric collections for fungi in the genus *Fusarium*. Immediately following a sampling flight, the exposed plates were removed from the UAV and placed in small plastic containers for transport to the laboratory. The plates were incubated for 5–7 days at room temperature to allow white, fuzzy colonies of *Fusarium* to develop. Colonies of *Fusarium* were counted and subcultured to plates of 1/4-strength potato dextrose agar (PDA) medium for further identification.

2.3 Statistical analyses

We hypothesized that the recovery of fusaria would typically not vary significantly across consecutive

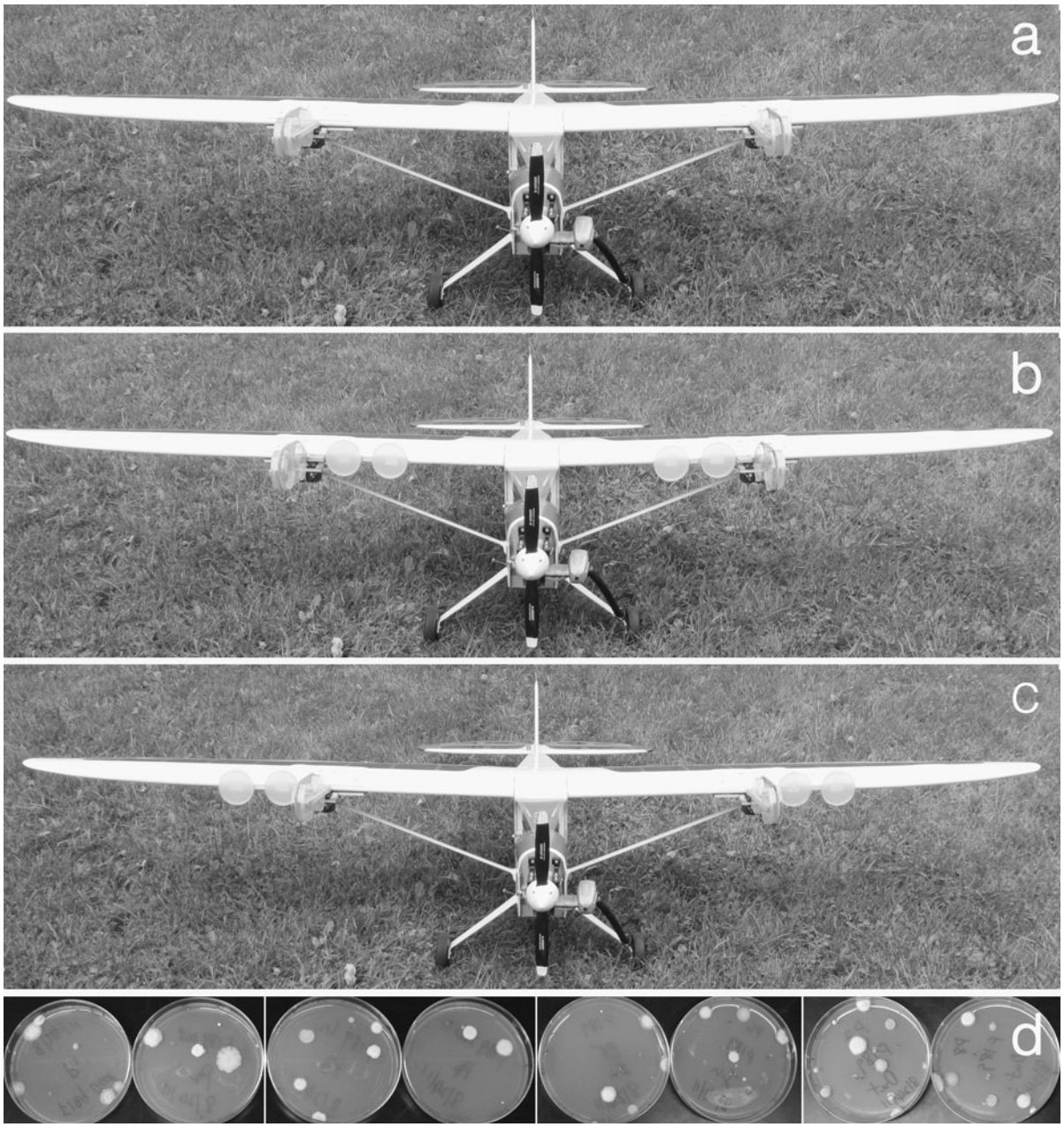

Fig. 1 An autonomous unmanned aerial vehicle (UAV) equipped with an array of eight microbe-sampling devices with four inner sampling arms and four outer sampling arms. Each arm carries two Petri plates containing a Fusarium selective medium. During takeoff and landing, the sampling devices are closed (**a**). After reaching the target altitude of 100 m, the inner sampling arms are opened for 10 min (**b**). These inner arms are closed, and the outer arms are opened for 10 min immediately following the first collection (**c**). Colonies of *Fusarium* are recovered in the laboratory and recorded for each of the plates (shown here from flight F189) (**d**)

aerobiological sampling intervals of short duration (a 10-min sample on the inner arms, immediately followed by a separate 10-min sample on the outer arms). If we fail to reject this hypothesis, then large fluctuations in the recovery of fusaria over short-to-intermediate timescales could be attributed to a suite of factors, such as the passage of LCSs (ATBs) and/or the contribution of a strong local source. By "short"

timescale, we mean short compared with the Lagrangian timescale, discussed below. It is also important to note that since the atmosphere is moving, short timescales are also related to short spatial scales. To test our hypothesis, colony counts of *Fusarium* obtained from different flights were assembled to perform statistical analyses (Tables 1, 2). For flights with simultaneous inner and outer arm sampling (Table 1), we estimated the variability in sampled colony counts of *Fusarium*, yielding an estimate of error for colony counts. For flights with consecutive inner and outer arm sampling (plates exposed during consecutive 10 min sampling periods). (Table 2), a simple linear regression was used to determine the relationship between colony counts of *Fusarium* collected for the inner and outer sampling arms. A scatter plot and a frequency plot were also used to show this relationship. Statistical analyses were performed using JMP 4.0. The correlation between colony counts from the inner and outer sampling arms was also explored as a function of time lag between sampling intervals (i.e., comparisons of colony counts between consecutive flights separated by 10 min and between other flights separated by longer periods throughout a sampling day).

3 Results

3.1 Simultaneous sampling with eight plates

In order to compare samples collected from inner and outer arms during *different* time periods, it is essential to show that samples do not vary significantly between inner and outer arms during the *same* time period. In other words, we must examine the potential role (if any) that plate position on the UAV has on the recovery of fusaria. To do this, we conducted 21 simultaneous sampling flights in which all eight sampling devices (inner and outer sampling arms opened at the same time) were exposed during the same sampling interval (Table 1). For these 21 flights, 433 colonies were recovered across all 21 sampling intervals; 234 colonies were collected across the inner arms, and 199 colonies were collected across the outer arms. Results of our correlation analysis for this

Table 1 Colony counts of *Fusarium* from simultaneous sampling (inner arms and outer arms were opened at the same time) with UAVs 100 m above ground level at Virginia Tech's Kentland Farm

Flights	Date	Time open (in and out)	Time closed (in and out)	Counts in[a]	Counts out[b]	Time sampling (min)
F137	10-Mar-10	0929	0944	3	1	15
F138	10-Mar-10	1035	1042	1	8	7
F139	10-Mar-10	1130	1145	7	4	15
F140	10-Mar-10	1300	1315	5	2	15
F141	10-Mar-10	1400	1415	4	9	15
F142	11-Mar-10	1005	1020	3	3	15
F143	15-Jul-10	0950	1005	23	16	15
F144	15-Jul-10	1155	1210	35	37	15
F145	16-Jul-10	0925	0940	20	26	15
F146	16-Jul-10	1045	1100	27	23	15
F147	28-Sep-10	0959	1014	2	3	15
F148	28-Sep-10	1118	1133	6	2	15
F149	28-Sep-10	1412	1427	17	8	15
F150	28-Sep-10	1532	1540	9	6	8
F151	29-Sep-10	0915	0926	3	7	11
F152	29-Sep-10	1029	1044	4	1	15
F153	29-Sep-10	1323	1338	7	6	15
F154	01-Oct-10	0908	0923	8	3	15
F155	01-Oct-10	1203	1218	9	8	15
F156	01-Oct-10	1428	1443	31	20	15
F157	01-Oct-10	1700	1708	10	6	8

[a] Counts from plates on the inner sampling arms of the UAV

[b] Counts from plates on the outer sampling arms of the UAV

Table 2 Colony counts of *Fusarium* from consecutive (a 10-min sample on the inner arms, immediately followed by a separate 10-min sample on the outer arms) aerobiological sampling intervals with UAVs 100 m above ground level at Virginia Tech's Kentland Farm in 2010 and 2011

Flights	Date	Open (in)	Closed (in)	Open (out)	Closed (out)	Counts in[a]	Counts out[b]	Time sampling out (min)	Time sampling in (min)
F158	06-Apr-11	0913	0923	0923	0933	6	10	10	10
F159	06-Apr-11	1027	1037	1037	1046	14	12	10	9
F160	06-Apr-11	1557	1607	1607	1616	18	26	10	9
F161	07-Apr-11	0952	1002	1002	1012	27	33	10	10
F162	07-Apr-11	1344	1354	1354	1404	16	13	10	10
F163	07-Apr-11	1514	1524	1524	1534	15	11	10	10
F164	07-Apr-11	1611	1621	1621	16:31	9	13	10	10
F167	08-Apr-11	1407	1422	1422	1435	5	9	15	13
F168	08-Apr-11	1510	1520	1520	1530	4	5	10	10
F169	11-Apr-11	0952	1002	1002	1012	22	21	10	10
F171	16-May-11	1449	1459	1459	1509	7	7	10	10
F173	18-May-11	1426	1436	1436	1446	2	1	10	10
F174	18-May-11	1600	1610	1610	1620	4	2	10	10
F175	19-May-11	0943	0953	0953	1003	4	5	10	10
F176	19-May-11	1045	1055	1055	1105	2	3	10	10
F177	19-May-11	1152	1202	1202	1212	1	2	10	10
F178	19-May-11	1312	1322	1322	1332	3	2	10	10
F179	19-May-11	1435	1445	1445	1455	6	3	10	10
F180	22-Aug-11	1000	1010	1010	1020	1	3	10	10
F181	22-Aug-11	1224	1234	1234	1244	3	2	10	10
F182	23-Aug-11	0942	0952	0952	1002	2	2	10	10
F183	23-Aug-11	1040	1050	1050	1100	2	2	10	10
F184	23-Aug-11	1149	1159	1159	1209	2	3	10	10
F185	23-Aug-11	1309	1319	1319	1329	4	5	10	10
F186	23-Aug-11	1424	1434	1434	1444	2	2	10	10
F187	23-Aug-11	1601	1611	1611	1621	4	5	10	10
F188	24-Aug-11	0915	0925	0925	0935	2	2	10	10
F189	24-Aug-11	1031	1041	1041	1051	4	5	10	10
F190	24-Aug-11	1159	1209	1209	1219	4	6	10	10
F191	24-Aug-11	1314	1324	1324	1334	4	5	10	10
F192	24-Aug-11	1426	1436	1436	1446	5	7	10	10
F193	25-Aug-11	0914	0924	0924	0934	1	2	10	10
F195	25-Aug-11	1200	1210	1210	1220	2	5	10	10
F197	26-Aug-11	1115	1125	1125	1135	3	2	10	10
F198	26-Aug-11	1313	1323	1323	1333	3	5	10	10
F199	26-Aug-11	1419	1429	1429	1439	7	12	10	10
F200	24-Oct-11	1018	1028	1028	1018	3	3	10	10
F201	24-Oct-11	1133	1143	1143	1153	4	5	10	10
F202	24-Oct-11	1303	1313	1313	1323	6	5	10	10
F203	24-Oct-11	1418	1428	1428	1438	5	4	10	10
F204	24-Oct-11	1530	1540	1540	1550	6	7	10	10
F205	25-Oct-11	0915	0925	0925	0935	1	2	10	10

Table 2 continued

Flights	Date	Open (in)	Closed (in)	Open (out)	Closed (out)	Counts in[a]	Counts out[b]	Time sampling out (min)	Time sampling in (min)
F206	25-Oct-11	1031	1041	1041	1051	3	6	10	10
F207	25-Oct-11	1200	1210	1210	1220	80	31	10	10
F208	25-Oct-11	1316	1326	1326	1336	12	120	10	10
F210	25-Oct-11	1543	1553	1553	1603	8	6	10	10
F211	26-Oct-11	0956	1006	1006	1016	3	3	10	10
F212	26-Oct-11	1205	1215	1215	1225	1	2	10	10
F213	26-Oct-11	1316	1326	1326	1336	8	9	10	10
F214	26-Oct-11	1432	1442	1442	1452	4	4	10	10
F215	27-Oct-11	0858	0908	0908	0918	3	3	10	10

[a] Counts from plates on the inner sampling arms of the UAV

[b] Counts from plates on the outer sampling arms of the UAV

sampling method showed that counts from the plates on the inner arms were positively correlated with counts from plates on the outer arms ($r = 0.89$, $P < 0.001$, $n = 21$). Thus, the location of the plates (inner versus outer sampling arms) did not impact the collection of fusaria.

We also used samples from this method to estimate the variation in colony counts for the inner and outer sampling arms. Considering only the 15-min samples of Table 1, we calculated the total colony count, c, and the magnitude of the difference between the inner and outer plates, which is the variation in colony counts, δc. In Fig. 2, we plot the fractional variation, $\delta c/c$, versus c and notice a trend. The curve corresponds to $1/\sqrt{c}$, the fractional standard deviation for a Poisson distribution. Thus, the probability of a viable airborne *Fusarium* spore impacting the samplers is well approximated as an inhomogeneous Poisson process with an arrival rate varying on a timescale long compared to the sampling duration. Thus, when a colony count, c, is obtained, the margin of error can be approximated as $\pm\sqrt{c}$.

3.2 Consecutive sampling with four inner plates and four outer plates

To determine whether the collections of fusaria varied between consecutive 10 min sampling periods, we conducted 102 consecutive sampling intervals (51 flights) 100 m above ground level in 2010 and 2011 (Table 2). Five hundred and eighty seven colonies were recovered across all 102 sampling intervals; 275 colonies were collected across the inner arms, and 312 colonies were collected across the outer arms (excluding flights F207 and F208, which were clear outliers in the dataset). A significant positive correlation was observed for colony counts of *Fusarium* between the inner plates and the outer plates ($r = 0.93$, $P < 0.001$, $n = 98$). Scatter plots and a simple linear regression of consecutive sampling intervals are shown in Fig. 3. Two flights, however, F207 and F208 (Table 2), were excluded from the scatter plot, since these flights were considered

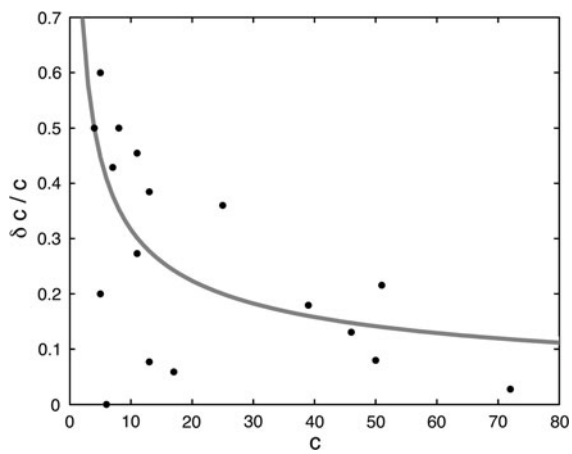

Fig. 2 Fractional variation in sampled colony counts of *Fusarium* (c is the total colony counts from inner and outer plates, and δc is the variation in colony counts) based on simultaneous sampling using inner (4 plates) and outer (4 plates) arms of a UAV during 15 min sampling periods. Flights were conducted 100 m above ground level during 2010. The probability of a viable airborne *Fusarium* spore impacting the samplers is approximated as a slowly varying inhomogenous Poisson process

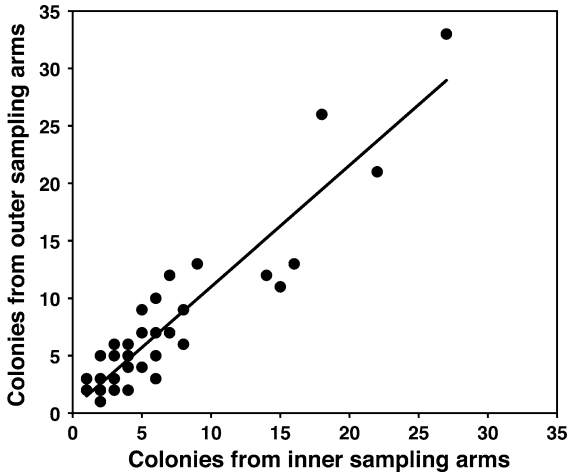

Fig. 3 Scatter plot and simple linear regression of consecutive sampling of *Fusarium* with inner (4 plates) and outer (4 plates) arms of a UAV. A significant correlation ($r = 0.93$, $P < 0.001$, $n = 98$) was observed between colony counts of *Fusarium* from the inner and outer arms. Flights were conducted 100 m above ground level during 2010 and 2011. Flights F207 and F208 were outliers and were removed from the analysis

outliers and are the subject of additional discussion below. It should still be noted, however, that when these flights were included in the correlation analysis, a significant positive correlation was still observed ($r = 0.38$, $P < 0.01$, $n = 102$). A frequency plot showed that the distribution of colony counts was similar for the inner and outer sampling arms over the range of colony counts (Fig. 4).

The correlation between colony counts from the inner and outer sampling arms was also explored as a function of time lag, τ, between sampling intervals. This approach allowed us to examine the temporal variation of colony counts. From Table 2 (excluding F207 and F208), pairwise comparisons of colony counts were determined for five time intervals: 0.17 h ($n = 49$ pairs), 0.5–1.5 h ($n = 83$ pairs), 1.5–3 h ($n = 94$ pairs), 3–6 h ($n = 84$ pairs), and 6–9 h ($n = 16$ pairs). An autocorrelation coefficient was determined as follows (autocorrelation coefficient for zero time lag is defined as 1):

$$R(\tau) = \frac{E[(c_t - \mu)(c_{t+\tau} - \mu)]}{\sigma^2}$$

where c_t is the colony count at time t, $c_{t+\tau}$ is the colony count at time $t + \tau$, μ represents the mean value, σ represents the standard deviation of the colony counts, and $E[\bullet]$ represents expectation value. The results of this analysis are shown in Fig. 5; the similarity between collections of *Fusarium* decreases over time. Error bars were calculated using results from Sect. 3.1 with the assumption that colony counts are Poisson distributed. A Gaussian distribution weighted method was used to obtain the error bars with sufficient number of simulations converging to a constant limit.

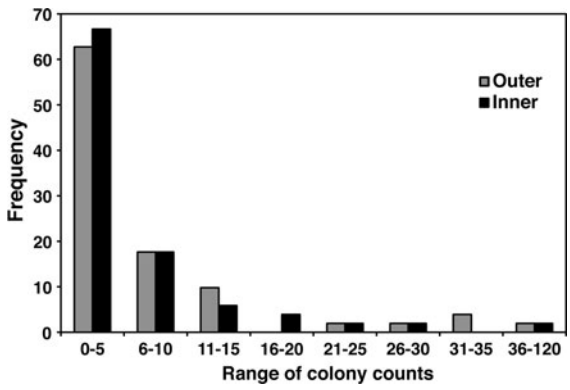

Fig. 4 Frequency plot of colony counts of *Fusarium* from consecutive 10 min sampling periods. Flights were conducted 100 m above ground level during 2010 and 2011. The plot shows that the distribution of colony counts was similar for the inner and outer sampling arms over the range of colony counts

3.3 Anomalous punctuated changes in colony counts for two consecutive flights

In flights F207 and F208, we observed a significant departure from the usual 10-min time-lag correlation.

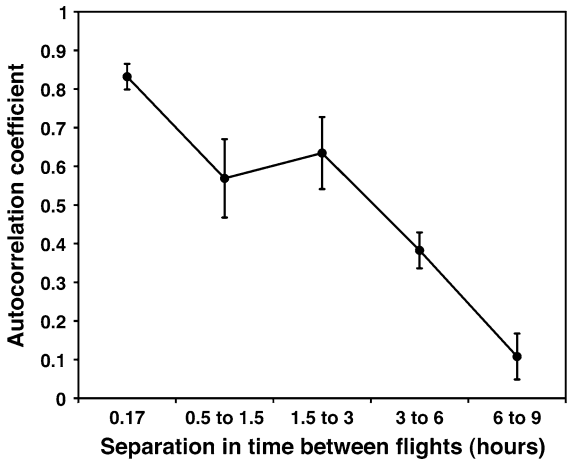

Fig. 5 The colony count autocorrelation coefficient $R(\tau)$ versus the time lag τ between sampling intervals. A high correlation is observed for a small time lag. The similarity between collections decreases over time; typical behavior for Lagrangian trajectories of particles (spores) in atmospheric turbulence

Flight 207 started sampling at 12:00 p.m. on October 25, 2011. Eighty colonies were recovered from the inner arms, but only 31 colonies were recovered from the outer arms. Flight 208 started sampling at 1:16 p.m. on the same day. Twelve colonies were recovered from the inner arms, but 120 colonies were recovered from the outer arms. The inner and outer samples from these flights were not correlated and cannot be explained by the statistics of a slowly varying inhomogeneous Poisson process. We view these two flights as anomalies that are in need of further explanation. We hypothesized that an ATB could have contributed to the observed changes in colony counts (e.g., Tallapragada et al. 2011), but archived weather-based computations did not reveal the presence of any strong LCSs (data not shown). Furthermore, HYSPLIT back trajectories for these samples suggested that all of these samples originated from a similar location in West Virginia (within the scale of accuracy of the computations, on the order of 10–100 km) (Fig. 6).

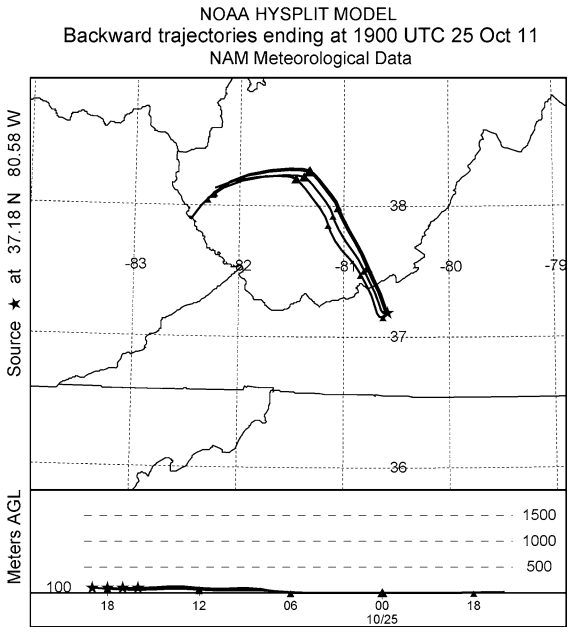

Fig. 6 HYSPLIT backward trajectories for flights 207 and 208 on based on Oct 25, 2011. Trajectories were calculated hourly for 1600–1900 UTC and suggest that all of the samples originated from a similar location in West Virginia (within the scale of accuracy of the computations, on the order of 10–100 km)

4 Discussion

Recent work has highlighted the role of Lagrangian coherent structures (LCSs) in the movement of fusaria in the lower atmosphere (Schmale et al. 2012; Tallapragada et al. 2011). Here, we extend this work by examining the relationship between the length of atmospheric sampling intervals with autonomous unmanned aerial vehicles (UAVs) and the recovery of fusaria. UAVs were equipped with an array of eight microbe-sampling devices with four "inner" sampling arms and four "outer" sampling arms. Each set of arms was used to collect consecutive aerobiological samples for 10 min sampling periods at 100 m above ground level at Kentland Farm in Blacksburg, Virginia. A total of 102 consecutive sampling intervals (51 flights) was conducted in 2010 and 2011. Results showed that the counts of fusaria did not vary across consecutive aerobiological sampling intervals. This work supports the idea that atmospheric populations of fusaria are well mixed, and large changes in the recovery of fusaria in the lower atmosphere may be attributed to large-scale phenomena (e.g., LCSs) operating across varying temporal and spatial scales.

Counts of *Fusarium* were not significantly different between plates located on inner and outer sampling arms in which all eight sampling devices were exposed during the same sampling interval. Thus, collections of *Fusarium* with UAVs were not influenced by the position of the plates. Random collections of *Fusarium* across all of the sampling surfaces are consistent with the idea that atmospheric populations of *Fusarium* are well mixed (Schmale et al. 2006). The fractional variation in colony counts revealed that the statistical distribution of colony counts across the inner and outer sampling arms is well approximated by a slowly varying inhomogeneous Poisson process. Colony counts from consecutive sampling intervals separated by 10 min did not vary significantly, but the correlation drops to nearly zero for flights separated by 9 h. The Lagrangian (autocorrelation) timescale,

$$T_L = \int_0^\infty R(\tau)d\tau,$$

is approximately 3 h, which is on the order ($\sim$10,000 s) estimated for velocity autocorrelations in atmospheric turbulence (Gifford 1987), and is also the Lagrangian timescale for layer (stratus) clouds.

The time T_L provides the timescale for the variation of the arrival rate for the slowly varying inhomogeneous Poisson process assumption, and we note that this is indeed long compared with the sampling duration (10 min), further justifying the Poisson assumption. For purely stochastic motion, the autocorrelation is an exponential, $R(\tau) = \exp(-\tau/T_L)$ (Csanady 1973; Dosio et al. 2005). With horizontal winds on the scale of 2–10 m/s, this timescale suggests that there are coherent "clouds" of *Fusarium* with horizontal dimensions on the scale of 20–100 km. This idea is consistent with the observations of Tallapragada et al. (2011) based on mesoscale atmospheric simulations, who found that the typical size for a coherent air mass was on a similar scale (50–150 km), based on the average passage of an LCS over the sampling location every 5–7 h.

Tallapragada et al. (2011) showed that LCSs (atmospheric transport barriers or ATBs) were correlated with changes in atmospheric counts of *Fusarium*. Schmale et al. (2012) suggested that LCSs were likely to influence the population structure of *F. graminearum*. With the exception of flights 207 and 208, we did not observe any significant variation in colony counts among consecutive sampling flights. Thus, we are now able to exclude fluctuations over short periods of time as potential contributors to changes in the atmospheric counts of *Fusarium*. Thus, large changes in the populations of *Fusarium* in the lower atmosphere may be attributed in part to large-scale phenomena (such as LCSs) or strong local sources operating across varying temporal and spatial scales.

The inner and outer samples from flights F207 and F208 were not correlated and represented a significant departure from the usual 10-min time-lag correlation. Archived weather-based computations did not reveal the presence of any strong LCSs, and HYSPLIT back trajectories for these samples suggested that they both originated from a similar same location in West Virginia (Fig. 6). Less than 90 min separated the start of F207 and the end of F208, but there was significant variation over a timescale of 10 min during both flights. This suggests a patchy (heterogeneous) distribution of *Fusarium* in the atmosphere (Okubo and Levin 2001). With the horizontal wind speeds at that time being approximately 2 m/s at ground level, the patchiness spatial scale was at most 1 km over a cloud on the order of 10–20 km (bracketed by the more typical flights F206 and F209). It is possible that these high values were triggered by a local and possibly temporally non-uniform source. Future work aimed at identifying the species recovered in these flight populations may provide clues about the approximate origin and mixing of these populations.

Future work by our research team aims to examine meteorological events that might provide signatures for the life history of populations of *Fusarium* in the lower atmosphere. Such work may contribute to an increased understanding of the spread of plant diseases in the future (Aylor 2003).

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