Chapter

The Physiological Ecology of White-Nose Syndrome (WNS) in North American Bats

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Abstract

White-nose Syndrome (WNS) is an emergent mycosis in North America that is caused by a severe cutaneous infection with the fungus *Pseudogymnoascus destructans* (*Pd*) during hibernation. *Pseudogymnoascus destructans* (*Pd*) was first observed in North America at a single site during the winter of 2006–2007 and has since spread to 39 U.S. States and 7 Canadian provinces. This fungus was introduced to North America from Europe, where it is endemic. WNS has thus far been observed to occur only in hibernating bats and has caused the populations of 4 North American bat species to decline by more than 84% within 7 years. Field studies have revealed that 4 other North American bat species are not afflicted with WNS when hibernating in areas where *Pd* occurs. The physiological and biochemical adaptations that permit some bat species to resist *Pd* infections are starting to be elucidated but are still poorly understood. A total of 47 different bat species are found in North America, about half of which hibernate during the winter. The potential future effects of WNS on 13 of these hibernating bat species remains to be determined.

Keywords: mycosis, hibernation, immunity, *Pseudogymnoascus destructans*, lipids

1. Introduction

White-nose Syndrome (WNS) is an emergent mycosis that affects some bat species in North America and is caused by an extensive cutaneous infection with the fungus *Pseudogymnoascus destructans* (*Pd*) during hibernation. It was first observed at a single cave in New York State during the winter of 2006–2007, and then spread to 5 more caves/mines in New York State during the winter of 2007–2008 [1]. *Pseudogymnoascus destructans* (*Pd*) has since spread to 39 U.S. States and 7 Canadian provinces, and it was introduced to North America from Europe [2]. This fungus grows on the muzzle, wings, and ears of afflicted bats during hibernation, with hyphae penetrating both the epidermis and dermis, consuming hair follicles, sebaceous and sweat glands [3–5]. *Pseudogymnoascus destructans* grows at ambient temperatures ranging from 1.9 to 15°C, although the hyphal morphology of this fungus exhibits heat stress at an ambient temperature (T_a) > 12°C, and growth ceases altogether at T_a > 19°C [6]. The arrival of *Pd* has led to severe population declines for 4 of the 6 bat species that hibernate in the Northeastern United States and Canada. Within 1–2 years after the arrival of *Pd* at a hibernation site, the number of little brown (*Myotis lucifugus*), northern long-eared (*Myotis septentrionalis*), Indiana

(*Myotis sodalis*), and tricolored (*Perimyotis subflavus*) bats decreases by 75–95% due to high over-winter mortality during the hibernation period [7]. Extensive cutaneous infections with *Pd* have been shown to be the cause of WNS in laboratory inoculation/hibernation experiments with captive *M. lucifugus* [8]. Bats suffering from WNS have numerous skin lesions caused by *Pd* infections on their wings, face, and ears. These *Pd* lesions display an orange-yellow fluorescence when illuminated by long-wave (365–385 nm) UV light [9]. The mechanism by which an extensive cutaneous infection with *Pd* leads to WNS and subsequent death during hibernation in some North American bat species is due to the effects of these infections on the hibernation energetics of small bats.

2. Hibernation physiology and white-nose syndrome

Mammals and birds are unique among animals in that they are homeothermic endotherms, maintaining a constant core body temperature (T_b) over a wide range of ambient temperatures (T_a) through a high metabolic rate [10]. Prolonged periods of high metabolic heat production by mammals and birds requires high rates of energy intake. Food availability in the wild often fluctuates, and consequently the energetic costs of maintaining a high T_b (32–42°C) via endothermy becomes prohibitively expensive during certain environmental conditions. Not all mammals and birds are permanently homeothermic, but instead enter periods of torpor [11]. Torpor is a period when metabolic rate and T_b are greatly reduced. It involves the regulation of T_b at a new and substantially lower level, with a new minimum T_b being maintained. Torpor is a controlled reduction in metabolic rate, T_b, and a suite of physiological processes in endotherms [12]. Mammalian and avian species that employ torpor are therefore classified as heterothermic endotherms [11]. Metabolic rates during torpor can be less than 5% of basal metabolic rate with a corresponding T_b of just 0.5–1.0°C above ambient temperature (T_a) in most instances [13]. Mammals and birds generally employ one of two common patterns of torpor, depending upon species: prolonged torpor during hibernation, and daily torpor. Daily torpor occurs when a heterotherm has torpor bouts that are 3–12 h in duration. Hibernation is seasonal, usually from late summer/autumn to the following spring. Hibernators do not remain torpid continuously throughout the hibernation season; instead, bouts of torpor last from days to weeks, interrupted by brief periods of high metabolic rates and high T_b called arousal episodes. Hibernation is the most common pattern of torpor found in mammals. Numerous studies have revealed that daily torpor occurs in at least 42 bird species, and 78 mammalian species as well. At present, only 1 bird species (the Common Poorwill, *Phalaenoptilus nuttallii*) is known to hibernate, whereas hibernation has been document in about 100 mammalian species [14].

Stored triacylglycerols mobilized from white adipose tissue (WAT) are the primary energy source utilized during mammalian hibernation [15]. The periods of high metabolic rates and T_b known as arousal episodes normally account for 80–90% of stored lipids (energy) utilized during hibernation [16, 17], but their physiological function is poorly understood. A number of physiological/biochemical alterations that occur during torpor are reversed during arousal episodes. These alterations include dendritic retraction, leukocyte sequestration in secondary lymphatic organs, endocytosis, and protein degradation [18]. Periodic arousals from torpor thus serve to rectify physiological/biochemical imbalances that occur during torpor. Heterothermic mammals typically undergo an extensive period of feeding and fattening for several weeks prior to the onset of hibernation, during

which body fat levels increase by 4 to 7-fold. The body fat content of *M. lucifugus* increases from 7 to 27% body mass during the 2 months prior to hibernation [19, 20], for example.

The energetic constraints that normal arousal episodes place on the physiological ecology of hibernating bats are illustrated by examining the winter physiological ecology of one bat species that is now severely impacted by WNS, *M. lucifugus*. Although the normal arousal episodes of hibernating *M. lucifugus* are usually less than 1 h in duration, they nonetheless account for 80–90% of all energy utilized during hibernation by this species [21]. Each of these arousal episodes requires the utilization of about 110 mg of stored depot lipids [22]. The body mass of *M. lucifugus* at the onset hibernation averages 8.5 g, indicating that about 2.0 g of depot lipids (triacylglycerols) are stored by each bat to support the entire 190-d hibernation period [23]. If arousal episodes consume a total of at least 80% of the lipids utilized during the entire hibernation period, then about 1.6 g of the 2.0 g stored by *M. lucifugus* are required to fuel them. Hibernating *M. lucifugus* thus have enough stored energy to support only about 14–15 arousal episodes during the entire period. Free-ranging *M. lucifugus* hibernating at ambient temperatures of 5.5 to 12.0°C consequently have normal torpor bouts averaging 12.4 to 19.7 d in length [22, 24] which enables them to survive a 190-d hibernation period without depleting their energy reserves prior to the spring.

Studies on free-ranging *M. lucifugus* revealed that bats with extensive *Pd* infections arouse more frequently from torpor during hibernation, and consequently their torpor bouts were much shorter than the normal range of 12.4 to 19.7 d previously reported for this species. Individuals with extensive cutaneous *Pd* infections (lesions) had a mean (± SE) torpor bout duration of 7.93 ± 2.49 d between arousal episodes, whereas those with no *Pd* lesions had a mean torpor duration of 16.32 ± 6.65 d which was significantly longer [25]. This 51% reduction in torpor bout duration produced by extensive cutaneous *Pd* infections made arousal episodes more frequent, which increased the rate of energy expenditure during the entire hibernation period. This increased rate of energy expenditure during hibernation is WNS, which leads to the premature depletion of body fat reserves prior to the normal spring emergence from hibernation when food (arthropods) first becomes available, which in turn causes of death [26]. The mechanism by which a severe cutaneous infection with *Pd* increases the frequently of arousal episodes during hibernation is related to the degree of evaporative water loss from the skin surface. The normal rate of evaporative water loss (EWL) of bats is considerable during torpor, and it is thought that they periodically arouse from torpor to drink in order to restore their water balance [27]. Hibernating bats have been observed drinking during arousal episodes [28]. It thus has been proposed that the numerous skin lesions caused by severe *Pd* infections may increase the EWL of affected bats, which in turn would cause them to arouse from torpor more frequently to drink. Analyses of blood samples collected from both *Pd* infected and uninfected *M. lucifugus* during hibernation support this hypothesis [29, 30]. Laboratory inoculation/hibernation experiments with *M. lucifugus* revealed that the mean EWL rate of individuals with numerous cutaneous *Pd* lesions was 1.6-fold greater than that for bats with no *Pd* lesions [31]. Interpreting these findings together reveals that when cutaneous *Pd* infections result in numerous skin lesions, WNS is caused by a corresponding increase in the rate of cutaneous EWL, which in turns leads to both reduced torpor bout lengths and more frequent arousal episodes. This subsequently results in a greater rate of energy expenditure during hibernation that produces a premature depletion of body fat reserves during hibernation, before feeding can occur in the spring.

3. The susceptibility to *Pseudogymnoascus destructans*

Field studies on hibernating bats demonstrated that *P. destructans* is found throughout both Europe and Asia, appearing on the skin of these bat species with no apparent increases in over-winter mortality or WNS [32, 33]. The greater mouse-eared bat (*Myotis myotis*) of Europe has been shown to be highly resistant to cutaneous *Pd* infections in both field [34] and laboratory studies [35]. Examination of hibernation sites in Europe revealed *Pd* growing on the muzzles of 5 different European species during torpor: pond (*Myotis dasycneme*), greater mouse-eared bat (*M. myotis*), Daubenton's (*Myotis duabentonii*), Brandt's (*Myotis brandtii*), and lesser mouse-eared (*Myotis oxygnathus*) bats. Mass deaths were not observed at these sites, however, and there were no apparent disruptions in torpor bout duration [34]. Histological analyses of infected *M. myotis* revealed that the hyphae of *Pd* do not extend beyond the epidermis of this bat species, even after several months of hibernation [36]. Some bat species are thus more resistant to *Pd* infections than others, thereby avoiding WNS. Cutaneous *Pd* infections and some associated skin lesions have subsequently been observed in 11 different European and 2 Asia bat species during hibernation [32, 33], with no apparent disruptions in torpor bout length or mortality. These studies indicate that European and Asian species of hibernating bats have evolved a resistance to *Pd* that greatly reduces the extent to which this fungus can infect the skin, thereby reducing the number of lesions that appear during hibernation to the point where torpor bout length is not significantly affected.

A similar resistance to both *Pd* infections and subsequent WNS is displayed by 4 species of North American bats as well. Field studies demonstrated that big brown bats (*Eptesicus fuscus*) hibernating where *Pd* occurs have torpor bouts of normal duration, and usually survive the winter with depot fat remaining [37]. Laboratory hibernation experiments with *E. fuscus* also revealed that *Pd* does not extensively grow in the skin of this species during hibernation [38]. The Eastern small-footed bat (*Myotis leibii*) is also highly resistant to cutaneous infections with *Pd*. A survey of 42 bat hibernation sites in the USA revealed that the number of *M. leibii* at these locations declined on average by only 12% during the first several years since the first appearance of *Pd*, whereas the number of *M. lucifugus*, *M. septentrionalis*, and *P. subflavus* at these sites decreased by 75–98% during this same period [39]. The Southeastern myotis (*Myotis austroriparius*) is a hibernating species found in Southern USA. Examinations of hibernation sites for this species in Alabama reveal although *P. destructans* first appeared in this area during 2011, no increases in the over-winter mortality of *M. austroriparius* have been observed. The skin of 99 hibernating *M. austroriparius* was examined for both the presence *P. destructans* DNA on it, and the UV-florescent skin lesions characteristic of *Pd* infections. Although 77% of the bats tested had *Pd* DNA on their skin, none of them had *Pd* skin lesions [40]. These findings indicate that although *M. austroriparius* was exposed to propagules (spores) of *Pd*, this fungus did not invade the skin of this bat species during hibernation, thus WNS does not develop. The gray bat (*Myotis grisescens*) is listed as an endangered species by the U.S. Fish & Wildlife Service, and some populations hibernate in caves located in the U.S. state of Tennessee. *Pseudogymnoascus destructans* first appeared in these caves during 2013, and some of the *M. grisescens* hibernating in these areas were found to have *Pd* skin lesions. No mass mortality has been observed for this species during hibernation, however, and the number of *M. grisescens* hibernating in these caves has been increasing since 2013. The total number of *M. grisescens* hibernating at 3 Tennessee caves increased by 15.4% during between 2016–2017 and 2018–2019, and it increased by 2.9-fold

at another cave during this same period [41]. It therefore appears that the degree of *Pd* infection that occurs during hibernation by *M. grisescens* is not sufficient to cause WNS.

There is ample evidence that some populations of *M. lucifugus* in the Northeastern United States have evolved a greater resistance to cutaneous infections with *Pd*, thereby avoiding WNS. A mark/recapture study conducted by Reichard et al. [42] revealed that the over-winter survival rate of *M. lucifugus* at 8 hibernation sites where *Pd* occurs in the Northeastern USA was at least 5.4%, with some individuals surviving 4 consecutive winters. Another mark and recapture study with *M. lucifugus* hibernating at a site in Michigan revealed that some individuals have survived 7 consecutive winters at a site where *Pd* occurs [43]. Studies on hibernating free-ranging *M. lucifugus* conducted during the first several years after the appearance of *Pd* revealed that although most individuals developed severe *Pd* infections with a high density of skin lesions that resulted in WNS, some individuals developed only moderate *Pd* infections that produced far fewer skin lesions, avoiding WNS and surviving the winter. Furthermore, the mean (± SE) torpor bout duration of these individuals with fewer lesions was 13.96 ± 4.30 d, which was not significantly different from that observed for *M. lucifugus* hibernating with no cutaneous *Pd* infections [25]. The differences in torpor bout lengths between individual *M. lucifugus* hibernating at the same site where *Pd* is found is illustrated by the skin temperature (T_{skin}) recordings of 2 adult females hibernating at the Williams Preserve Mine in New York State during the November–December period of 2008 (**Figure 1**). Skin temperature is equivalent to body temperature in small bats [44]. The first bat (**Figure 1A**) began hibernation with torpor bouts that were normal in length (15–20 d), but torpor bout length decreased to just 7–9 d during December 2008, indicating that this individual had succumbed to WNS. The second *M. lucifugus* (**Figure 1B**) examined, however, maintained torpor bouts that were 15–20 d long throughout the study period, demonstrating that it was not afflicted with WNS.

These studies indicate that for *M. lucifugus*, some individuals within certain populations are more resistant to *Pd* infections than others, and these are the bats that are surviving consecutive winters despite the presence of *Pd*. The consistent survival of some *M. lucifugus* in the presence of *Pd* has led to a partial recovery of some populations in New York State. A small maternity colony of *M. lucifugus* in NY examined by Dobony and Johnson [45] during the summers of 2006 through 2017 demonstrated that the size of it decreased by 88% after the first appearance of *Pd*, then stabilized during 2010–2014, and has been increasing since 2014. The New York Department of Environmental Conservation has been conducting annual counts of hibernating bats at the Williams Preserve Mine and Hailes Cave since 1999. These are 2 of the 6 bat hibernation sites where *Pd* first appeared during the winter 2007–2008. The number of *M. lucifugus* hibernating at the Williams Preserve Mine during the winter of 2008–2009 was just 12% of that observed prior to the first appearance of *Pd*, and the number at Hailes Cave was just 9% of the pre-*Pd* level for this site. The number of *M. lucifugus* observed at these sites during subsequent hibernation periods has since consistently increased, however. The number of *M. lucifugus* increased to 41% of pre-*Pd* levels by 2017 at the Williams Preserve Mine, and increased to 31% of pre-*Pd* levels at Hailes Cave by 2017 [23]. Another field study conducted at the Williams Preserve Mine indicates that this *M. lucifugus* population has evolved a higher resistance to *Pd* growth on their wings [46].

A field study conducted at a single hibernation site in NY during the winter of 2014–2015, about 6 years after *Pd* had arrived, indicated that the mean (± SE) torpor bout duration of *M. lucifugus* surviving the winter was 12.0 ± 10.8 d [47], which

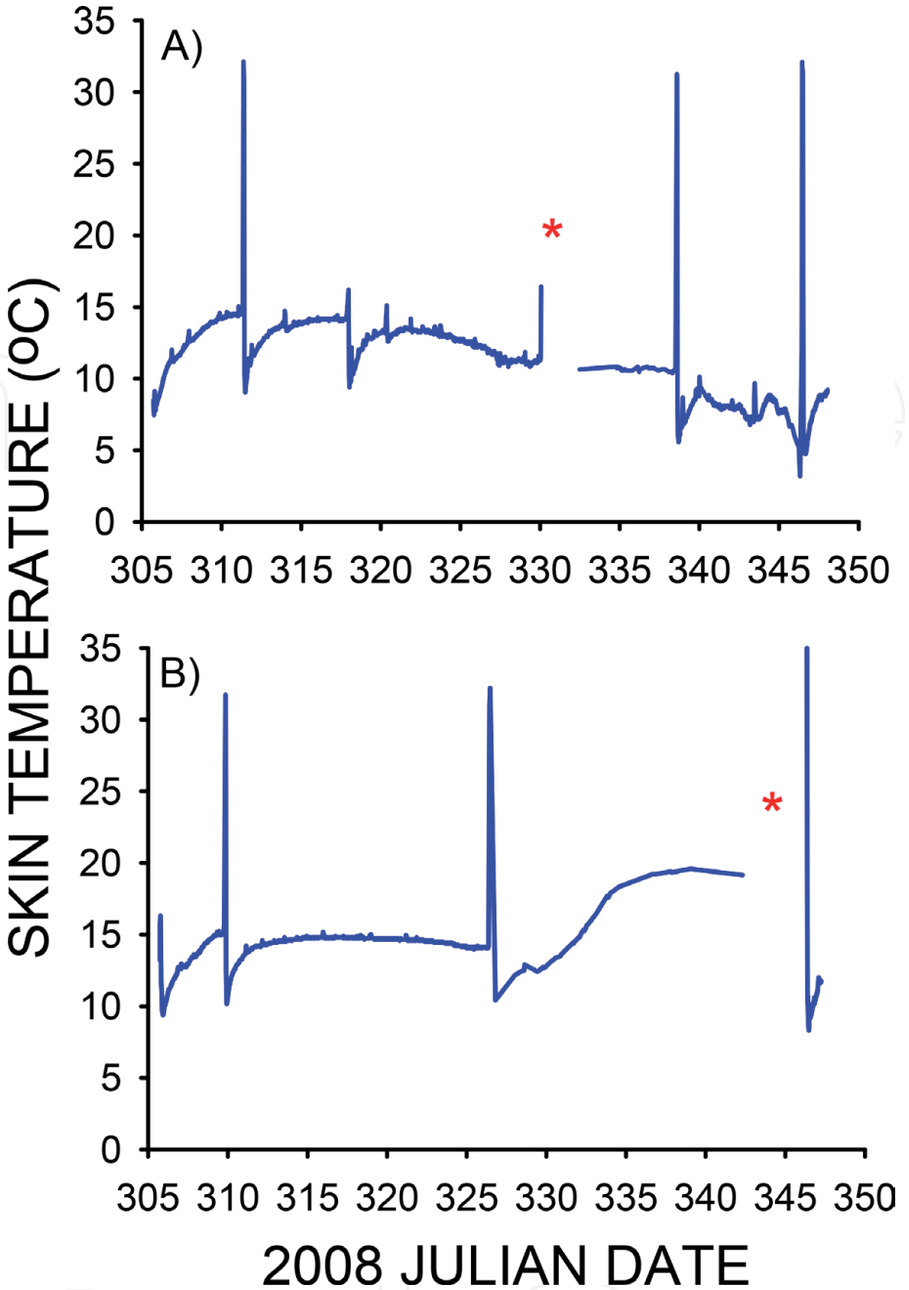

Figure 1.
*(A) Skin temperatures of two different female Myotis lucifugus hibernating at the Williams preserve mine during November and December 2008. (B) Recordings of T_{skin} began 45 min after a temperature-sensitive radio transmitter was placed on each bat during Julian day 305. Radio signals were continuously recorded at 10–15 min intervals, torpor is defined as when T_{skin} < 24°C. *indicates a period when the bat was out of the range of the automated radio receiver during an arousal episode. Data are from Frank et al. [23].*

is close to the normal torpor bout duration of 15–20 d previously reported for this species, thus indicating that most were hibernating normally. Another field study on *M. lucifugus* hibernating in the Williams Preserve Mine revealed that the bats hibernating at this site 1 year after the arrival of *Pd* (2008–2009) had: a) a mean torpor bout duration of 7.6 d, b) no depot fat reserves remaining by March, and c) an apparent over-winter mortality rate of 88%. The *M. lucifugus* hibernating at this same site 6–9 years after the arrival of *Pd*, in contrast, had: a) a mean torpor bout duration of 14.7 d, b) depot fat remaining in March, and c) an apparent over-winter mortality rate of 50% [23]. Interpreting these studies together reveals that some populations of *M. lucifugus* have recently evolved a greater resistance to cutaneous infections with *Pd*, thus reducing the frequency of WNS.

4. Impacts of WNS

The impact of WNS on the total number of *M. lucifugus* in North America has been drastic, despite the partial recovery of some populations in New York State. A recent analysis of winter hibernaculum counts for 5 bat species performed in 27 U.S. states and 2 Canadian over a 23-year period was performed by Cheng et al. [48]. Their analysis revealed that the total number of *M. lucifugus*, *M. septentrionalis*, and *P. subflavus* hibernating at these sites decreased by over 90% with the first 7 years after the arrival of *Pd*, and the number of *M. sodalis* decreased by 84%. The decline in the number of *M. septentrionalis* was so great that the U.S. Fish and Wildlife Service designated it a threatened species in 2016. A total of 47 different bat species are found in North America, and about half of them are known to hibernate during the winter [49]. Although the susceptibility of 8 of these hibernating bat species to WNS is well understood, the ability of *Pd* infections to cause WNS in other species of hibernating North American bats is virtually unknown. The National Wildlife Health Center of the U.S. Geological Survey thus began a WNS surveillance program in 2013 to address the potential effects of *Pd* as it spreads across the USA. Each year the wildlife agencies of 22 U.S. states submit thousands skin surface swabs collected from free-ranging bats during either the fall or hibernation to the National

Scientific name	**Common name**	*Pd* **susceptibility**
Myotis lucifugus	Little brown myotis	WNS
Myotis septentrionalis	N. Long-eared myotis	WNS
Myotis sodalis	Indiana myotis	WNS
Perimyotis subflavus	Tricolored bat	WNS
Myotis californicus	California myotis	Unknown
Myotis thysanodes	Fringed myotis	Unknown
Myotis evotis	W. Long-eared myotis	Unknown
Antrozous pallidus	Pallid bat	Unknown
Parastrellus hesperus	Canyon bat	Unknown
Myotis auriculus	Southwestern myotis	Unknown
Idionycteris phyllotis	Allen's big-eared bat	Unknown
Myotis leibii	Small-footed myotis	No WNS
Myotis austroriparius	Southeastern myotis	No WNS
Eptesicus fuscus	Big brown bat	No WNS
Myotis grisescens	Gray myotis	No WNS
Myotis ciliolabrum	Small-footed myotis	*Pd* DNA
Corynorhinus townsendii	Townsend's bat	*Pd* DNA
Lasionycteris noctivagans	Silver-haired bat	*Pd* DNA
Myotis yumanensis	Yuma myotis	*Pd* infection
Myotis volans	Long-legged myotis	*Pd* infection
Myotis velifer	Cave myotis	*Pd* infection

Table 1.
North American species of hibernating bats and their known levels of susceptibility to cutaneous infection with Pseudogymnoascus destructans.

Wildlife Health Center which are examined for *Pd* DNA. Skin biopsies collected from bats showing signs of fungal infection are also submitted for histological analyses [A. Ballman, personal communication]. The result of these surveys are summarized in the WNS webpage maintained by the U.S. Fish & Wildlife Service [50]. The degree to which each species of hibernating North America bat is susceptible to cutaneous *Pd* infections and WNS has been compiled in **Table 1** using both the results of both the surveys conducted by National Wildlife Health Center as well as the published studies cited previously. The susceptibility of 7 of the 21 bat species listed in **Table 1** to *Pd* infections during hibernation is currently unknown due to a lack of data for these species. The DNA of *Pd* has been found on the skin surface of *Myotis ciliolabrum*, *Corynorhinus townsendii*, and *Lasionycteris noctivagans* indicating that *Pd* now occurs with the range of these species, but it is not known if *Pd* can invade their skin and produce lesions. Skin lesions caused by *Pd* infections have been documented in hibernating *Myotis yumanensis*, *M. volans*, and *Myotis velifer*, but it is not known if the density of *Pd* lesions that appear during this period is sufficient to cause WNS. The degree of *Pd* infection that occurs in *Myotis austroriparius*, *M. grisescens*, *Myotis leibii*, and *E. fuscus* is not sufficient to cause WNS in these species.

5. Cutaneous lipids

Four of the hibernating bat species found in North America as well as 11 hibernating bat species in Europe limit the degree of cutaneous *Pd* infection to the point where it does not result in WNS during hibernation. The physiological and biochemical mechanisms that enable these bat species to reduce *Pd* infections are poorly understood. Several recent studies have revealed that one factor which confers a resistance to *Pd* infections is the lipid composition of the epidermis. The outermost stratum of the epidermis is the first defense against fungal skin infections because the mycelium must initially invade it, and leukocytes are not present in these epidermal layers. The epidermis is composed chiefly of special epithelial cells called keratinocytes that occur in 4 strata; they are produced in the deepest stratum (the stratum basale) and migrate to the top stratum (the stratum corneum) as they age. Epidermal surface lipids are a mixture of compounds secreted by keratinocytes into the intracellular matrix, and sebum secreted onto it by the sebaceous glands. The lipid mixture secreted by keratinocytes contains free sphingosine bases, ceramides, cholesterol, and free fatty acids (FFAs), whereas the sebum is composed of triacylglycerols, diacylglycerols, FFAs, wax esters, squalene, cholesterol, and cholesterol esters [51, 52]. The epidermal lipids of bats also have cerebrosides and monoacylglycerols [53, 54]. Some free fatty acids (FFAs) are known to have antimicrobial effects [55].

It has been demonstrated that the wing epidermis of both *M. lucifugus* and *E. fuscus* contain the same 7 fatty acids: Myristic (14:0), pentadecanoic (15:0), palmitic (16:0), palmitoleic (16:1), stearic (18:0), oleic (18:1), and linoleic (18:2) acids. The wing epidermis of hibernating *E. fuscus* contains about twice as much myristic, palmitoleic, oleic, and linoleic acids than that of *M. lucifugus*, as well. Laboratory experiments with *Pd* cultures revealed that pentadecanoic, palmitoleic, oleic, and linoleic acids in the free fatty acid (FFA) form inhibit the growth of *Pd* [56, 57], with linoleic acid reducing it by more than 99%. The results of one of these experiments are summarized in **Figure 2**.

Epidermal free fatty acid composition thus appears to be one of the factors that enables *E. fuscus* to better resist *Pd* infections than *Myotis lucifugus*.

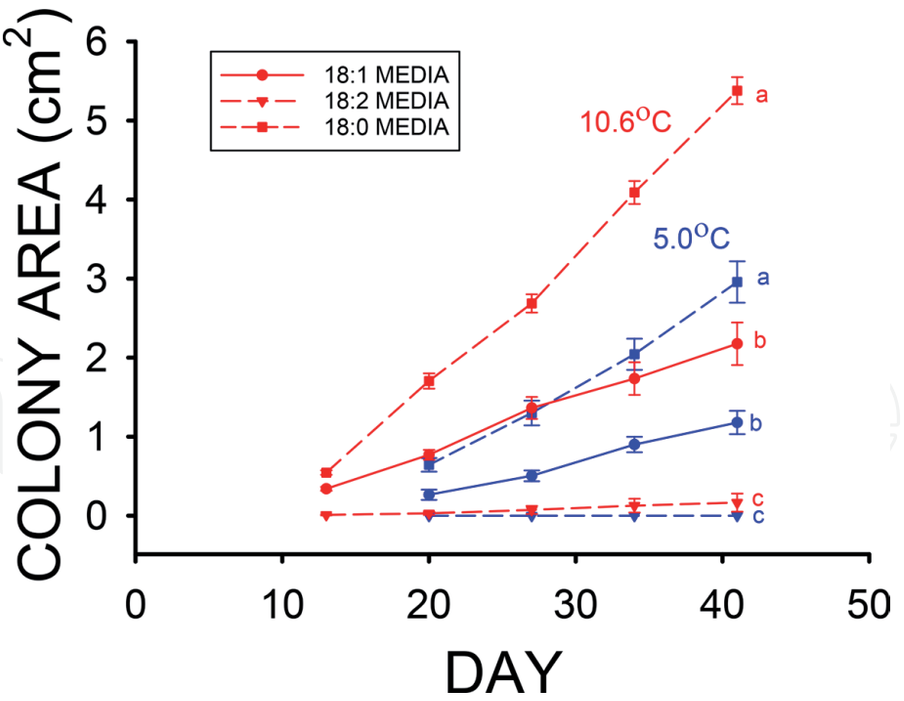

Figure 2.
Mean (± SE) surface areas of Pd colonies at various growth stages on media containing 1% of either oleic (18:1), linoleic (18:2) or stearic (18:0) acids, while being incubated at 5.0 (blue symbols) and 10.6°C (red symbols). Mean within the same temperature treatment sharing a common lower-case letter are not significantly different at the P < 0.05 level. Data are from Frank et al. [56].

Wax esters consist of an alcohol linked to a fatty acid molecule with an ester bond [58]. About 120 different wax esters have been found in the sebum of *Myotis myotis* during hibernation [59]. A recent study used laboratory *Pd* culture experiments to determine the effects of some of these wax esters on *Pd* growth [60]. These experiments have revealed that 4 of the wax esters found in the sebum of *M. myotis* inhibit *Pd* growth by over 90%. These anti-*Pd* wax esters are: behenyl linoleate, palmityl linoleate, arachidyl linoleate, and behenyl palmitoleate. One factor that enables *M. myotis* to resist *Pd* infections is therefore presence of these anti-*Pd* wax esters in their epidermis. Changes in epidermal lipid composition may also be one of the adaptations that permit some populations of *M. lucifugus* to now have a higher resistance to cutaneous *Pd* infections.

6. Conclusions

Four species of North American bats develop severe *Pd* infections during hibernation which result in WNS, whereas 4 other bat species develop only moderate *Pd* infections during this period and do not display the abnormal torpor patterns and mortality associated with WNS. It has been also demonstrated that within the same population of *M. lucifugus*, individuals with a high density of *Pd* lesion in their skin suffer from WNS, whereas those with a much lower density of *Pd* lesions do not. Cutaneous infections with *Pd* thus do not always result in WNS, and a certain density of *Pd* lesions must be present in the skin before WNS develops. The precise minimum *Pd* lesion density for WNS is not known, and it should be determined to better understand both the ecology and potential impacts of WNS on the hibernating bat populations of North America, as the mere presence of some *Pd* lesions alone does not indicate that a bat species/population is afflicted with WNS. The effects of these lesions on torpor bout length must be taken into consideration when

assessing potential WNS. The full extent to which *Pd* can infect the skin and causes WNS in 13 of 21 bat species listed in **Table 1** is not known. Most of these 13 bat species occur in Western North America. It is thus unclear how WNS will affect most Western bat species as *Pd* spreads across North America. If current trends in *Pd* susceptibility continue, then it is likely that WNS will severely affect 7–8 additional bat species in North America. Analyses of preserved museum specimens suggest that *Pd* has been associated with hibernating bats in Europe for over 100 years, whereas they reveal no evidence that *Pd* was present in North America bats between 1861 and 1971 [61]. It therefore appears that bats across Europe have adapted to *Pd* for over 100 years, and they are now highly resistant to *Pd* infections, thereby avoiding WNS. The physiological/biochemical basis of this resistance is largely unknown but warrants further investigation to better predict which New World bat species will be severely affected by WNS.

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Conflict of interest

The author declares no conflict of interest.

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