Study Report

Interference of Flying Insects and Wind Parks

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Stuttgart, 30.10.2018

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Summary

The study investigates possible coherence of flying insect losses recently discovered in Germany and insect impingement on the rotor blades of wind turbines.

Evidence from literature confirms that migrating insects select fast air streams above the turbulent surface layer of the atmosphere for the purpose of efficient displacement to breeding grounds. Wind farm developers select sites with strong winds and install high towers with rotors just above the surface layer in order to optimize the energy output of their wind turbines. As a result of this coincidence, large numbers of flying insects can be expected in wind farms.

Model calculation of the amount of insect biomass that traverses wind rotors during operation provides a first estimate of the order of magnitude of 24,000 tons of insects crossing the German wind park throughout the summer season. Based on conservative model assumptions, five percent of the insects flying through a rotor could be actually damaged. The related loss of 1,200 tons per year since more than fifteen years could be relevant for population stability.

Species flying at critical rotor heights between 20 and 220 meters above ground level in addition to those already found within this study should urgently be identified by DNA meta-barcoding of the deposits that are regularly found on rotor blades. In addition to that, wind farms should be enabled to recognize approaching insect swarms and to react accordingly for their protection and conservation.

Table of Contents

1. Introduction

The study examines the impact of wind farms on flying insects and provides first estimates of potentially affected biomass based on simplified models. While impact of wind farms on birds and bats has been investigated since many years (Barclay et al. 2007, Arnett et al. 2008), impact on flying insects has rarely been questioned up to now (Böttger et al. 1990).

The analysis was motivated by evidence from Hallmann et al. (2017) about more than 75% of flying insect biomass lost in several nature reserve areas of Northern Germany over the last decades, and by a similarly alarming publication of Corten and Veldkamp (2001) describing up to 50% loss of wind power capacity caused by insect deposits on rotor blades. Those facts suggest closer examination of a possible coherence of both phenomena, particularly because the impacts that contributed to insect losses are yet unknown (Figure 1, right).

As will be shown in the following, scientific literature about insect migration and about insect impingement on rotor blades strongly supports the hypothesis of such coherence while there is no evidence supporting negligibility of wind-power-related insect losses.

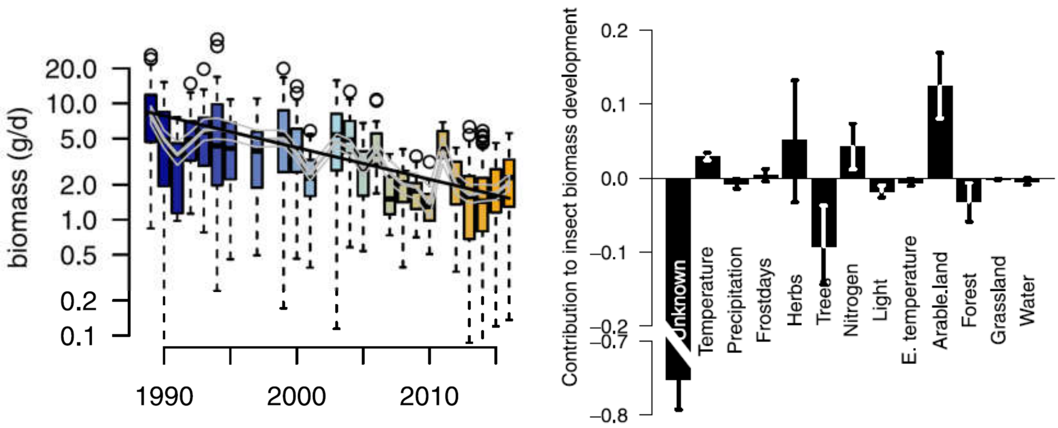

Figure 1: Left: More than 75% loss of flying insect biomass in nature reserve areas in Northern Germany since 27 years found by Hallmann et al. (2017). Right: statistical correlation of the registered losses with several possible impact factors related to insect population. More detailed analysis of the trend can be seen in Figure 2

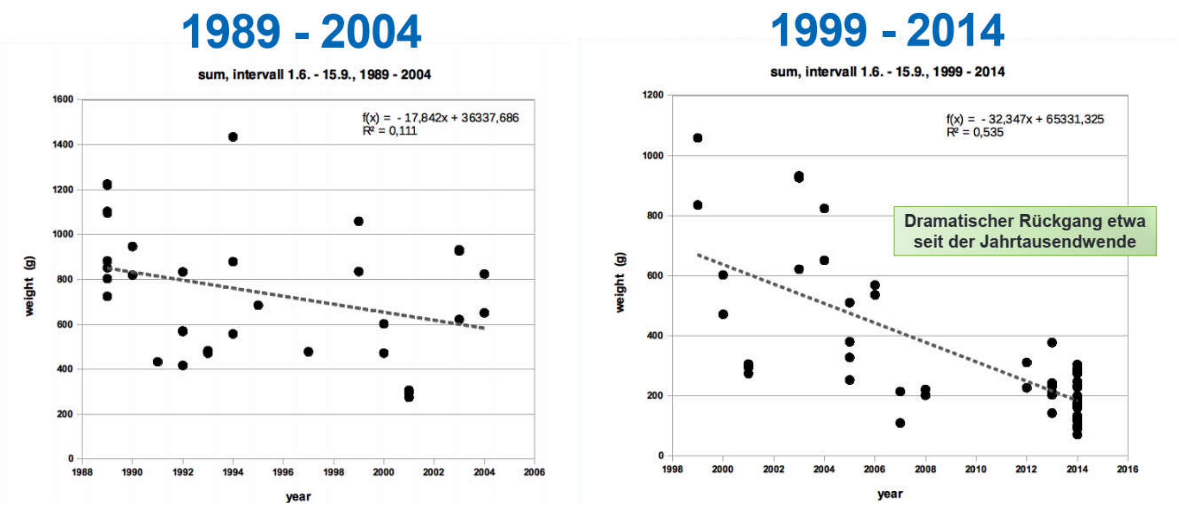

Figure 2: Insect biomass found in Malaise traps in Northern Germany from 1989 – 2014 (Deutscher Bundestag 2016). The figure at right reveals an acceleration of insect losses after the change of the century.

2. Evidence of conflicts between wind farms and insects

Section 2 provides information from literature about evidence of encounters of wind turbines and flying insects. Evidence includes proof of visible damage, a hypothesis about additional invisible damage, explanation of mechanisms that lead to an encounter of insects and rotor blades, proof of species at risk, a review of critical events in insect's life, additional hypotheses about insects being attracted by wind farms and missing proof of tolerability.

2.1 Visible deposits of flying insects on rotor blades

Residues of flying insects (Figure 3) have been reported over three decades to be found on rotor blades of wind power generators in different countries and regions (Böttger et al. 1990, Hinsch & Westermann 1996, Corten & Veldkamp 2001, Wilcox & White 2016, BladeCleaning 2017, Ehrmann et al. 2017, Wilcox et al. 2017).

Figure 3: Examples of insect residues found on wind rotor blades. Left: Deposits of a swarm of the beetle *Omophlus lepturoides* (BladeCleaning 2018). Center: Unidentified insect roughness on rotor blades (Wilcox et al. 2017). Right: Soiled leading edge of a rotor blade near to the blade tip (Hinsch & Westermann 1996).

Deposits on the blades can reduce the efficiency of wind power generation. For this reason the blades are regularly cleaned, if rainfall is not sufficient to achieve that. The mass of insects that are damaged by rotor blades every year has not yet been assessed or estimated.

Krishnan (2016) observed that insects that impact the surface at angles near 90° typically leave intact exoskeletons on the surface whereas those that impact at lower angles leave behind only a hemolymph residue. Wilcox et al. (2017) provide a theoretical framework for the quantification of insect collection efficiencies of different airfoils used for wind power generation under specific operation conditions. This theoretical framework is used later in this study to quantify potential damage of wind farms on insect population.

2.2 Additional risk from barotrauma and partial impact

Similar to the sides of the wing of an airplane, a wind rotor blade develops a low pressure area on its suction side and a high pressure area on the pressure side that create lift for its motion (Manwell et al. 2011, Phengpom et al. 2016). Air pressure can be up to 100 hPa lower than normal at the suction side close to the tip of a blade, and linearly change to normal pressure near the nacelle. Pressure reduction is proportional to the speed of the blades, which is highest at the tip and lowest at the nacelle. Insects traversing these low pressure areas will be exposed to a pressure change within a split second. The effects of such barotrauma are suspected to kill bats (Rollins et al. 2012, Voigt et al. 2015) but are unknown for insects. In contrast to bats and birds, insects affected by barotrauma or by partial impact of the blades on antennae, mouthparts, wings, legs or genitals will remain unperceived, as wind will carry them far away from the rotors before they reach the ground.

2.3 Insect migration in the atmospheric boundary layer

The following section examines why flying insects are under risk of being damaged by physical impact from wind rotors. The analysis is based on following evidence:

1. The flight level that bears the danger of meeting a wind rotor lies roughly between 20 meters above ground, which is the height of the lower rim of older, smaller machines, and 220 meters above ground which is the height of the upper rim of new, large machines (Figure 4). The outer rim of the rotors is the most dangerous region for flying insects, because rotor blade tips have a speed of about 80 ± 10 meters per second during operation (Amirzadeh et al. 2017). However, also surfaces near the nacelle are critical, as rupture velocities of e.g. house flies and fruit flies lie in the range of 12 and 14 m/s, respectively (Wilcox et al. 2016).

2. Visual observation, trapping and radar assessment show that many insect species fly at the critical height of modern wind rotors. A maximum of insect density is often detected close to or inside that range. Johnson (1957) and Drake (1984) provide empirical data for insect density as function of height, suggesting values roughly three to four times higher than average within the critical range of wind rotor heights (Figure 5).

3. The lowest part of the atmospheric boundary layer is the so-called surface layer. It is characterized by strong turbulence from wind shear and thermal convection. The height of this layer can vary from approximately 25 ± 15 meters above ground level at night to 80 ± 20 meters during daytime (Figure 6). In the layer above the surface layer, mixing of air masses occurs during daytime due to convectively driven updrafts and downdrafts up to 2000 m altitude. At night part of that layer becomes thermally stratified up to several hundred meters above ground with low turbulence and often relatively strong winds. Insects throughout all sizes and species seek to reach such layers above the surface layer for the purpose of fast and energy-efficient displacement during migration. Those layers could in fact be named “insect migration layers” (Figure 7).

For the purpose of migration, many insect species actively try to overcome the surface layer and reach the less turbulent winds beyond (Reynolds et al. 2017a). During daytime, convective plumes with vertical wind speeds of up to 5 m/s will help all kinds of insects to reach very high levels of the planetary boundary layer (Geerts and Miao 2005). Radar analysis has revealed up to one thousand times higher insect concentration within such plumes compared to the surroundings. Most of the smaller, passively flying insects will stay within such plumes and reach up to 1,000 meters or more above ground level before they start travelling with the wind in horizontal direction, which has been confirmed by the findings of Weidel (2008) and Geerts and Miao (2005).

In contrast to that, larger insects – especially when travelling at night without the help of convective plumes – may actively select lower layers for migration. As an example, in order to save energy and keep their body temperature balanced during flight, they may choose a layer with maximum wind speed and adequate air temperature. It is commonly known that insects usually avoid flying when there is strong wind and rain. This is reasonable behavior, as with high turbulence near the ground flight and navigation will be difficult. In that case they will prefer to hide and stay down. Migration will start during calm weather conditions when wind speed at ground level is fairly low. However, once insects reach above the surface layer, travelling speeds can vary between 20 and 100 km/h (5 - 25 m/s), taking them quickly and efficiently to distant places (Aralimarad et al. 2011). Unfortunately, this behavior brings them directly into the critical range of operating wind rotors.

Contreras and Frasier (2008) have analyzed signals from frequency-modulated continuous-wave (FMCW) cloud radar during summer on a site in Oklahoma, USA. They detected insects flying up to 2000 meters high and identified a maximum average insect density between 150 and 250 meters above ground level, “which results from dense layers of nocturnal insects”. While cloud radar does not work below 150 meters, daytime insect plumes reaching up to 1000 meters and down below 50 meters above ground level with insect densities up to 1,000 times higher than in the surrounding air were found by Geerts and Miao (2005) using an airborne 3 mm multi-antenna Doppler radar.

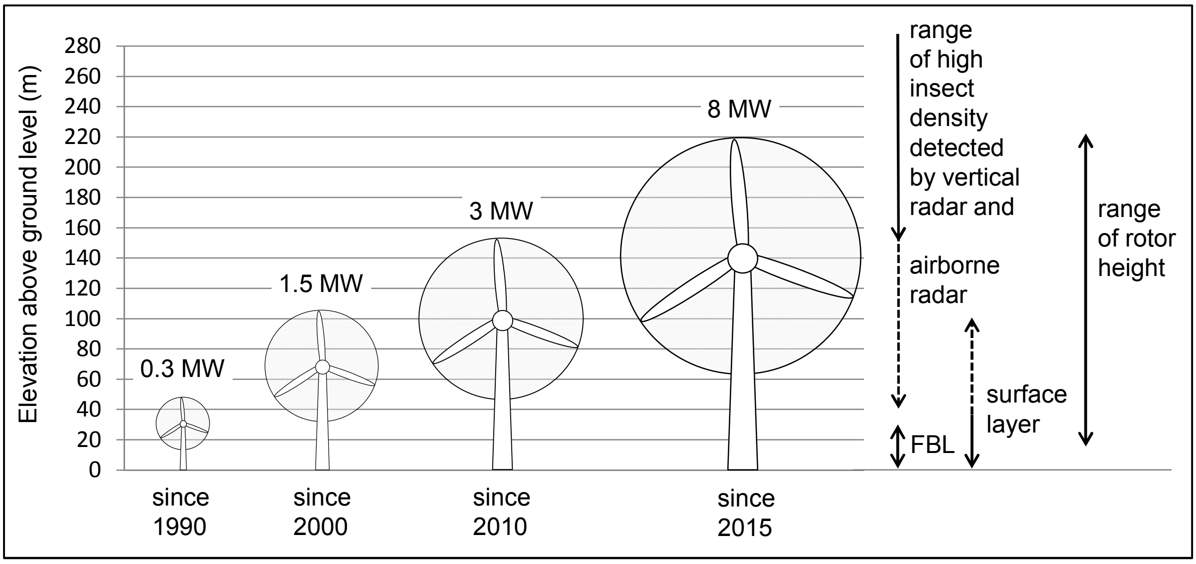

Figure 4: Development of wind turbine size and capacity since 1990 (based on Amirzadeh et al. 2017), range of rotor height, variable height of the turbulent surface layer of the atmosphere according to (Stull 1988) and the general flight boundary layer of insects (FBL) assumed by Keuper (1993). The figure also shows the range of high, in some cases maximum insect density detected by vertical entomological radar (Bell et al. 2013, Chapman et al. 2010, Hu et al. 2016), cloud radar (Contreras and Frasier 2008) and airborne radar (Geerts and Miao 2005). Please note that the lower registration limit of vertical radars and cloud radars lies around 150 meters above ground level.

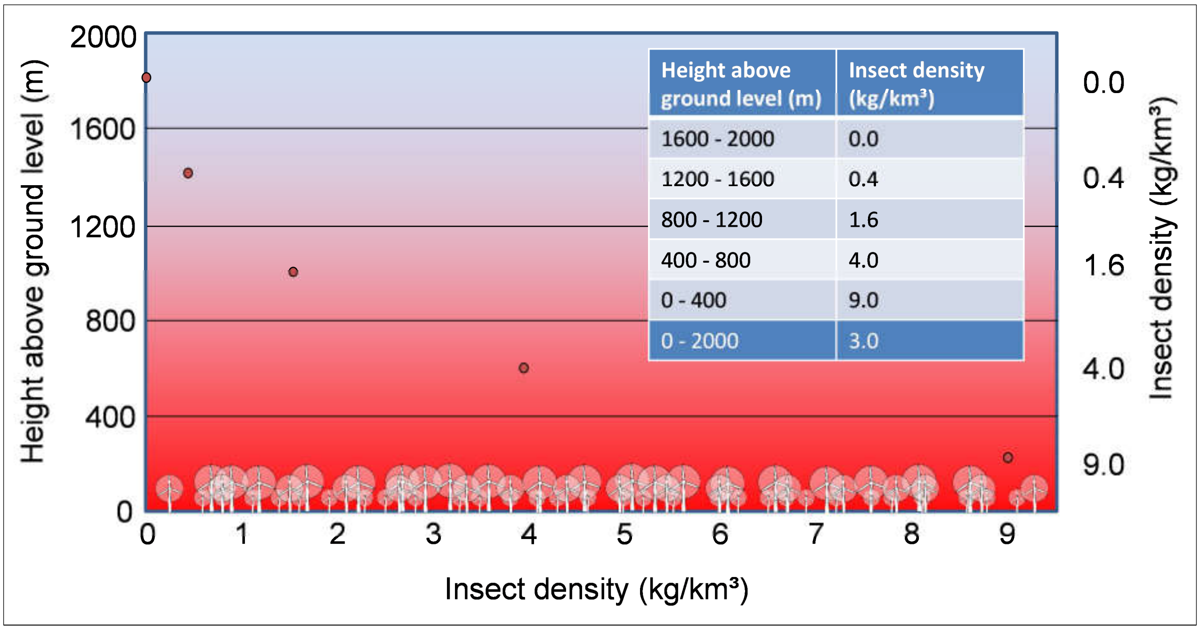

Figure 5: Model of vertical insect density distribution adapted from Johnson (1957) that shows average insect density in five layers of 400 meter thickness each. The average insect density over the total height up to 1750 meters above ground level found by Weidel (2008) was 3 kg/km³. He used airplane traps during regular flights in the warm season from 1998 to 2004. The related insect biomass density at rotor level (lowest layer) is assumed to be 9 kg/km³ in the year 2003.

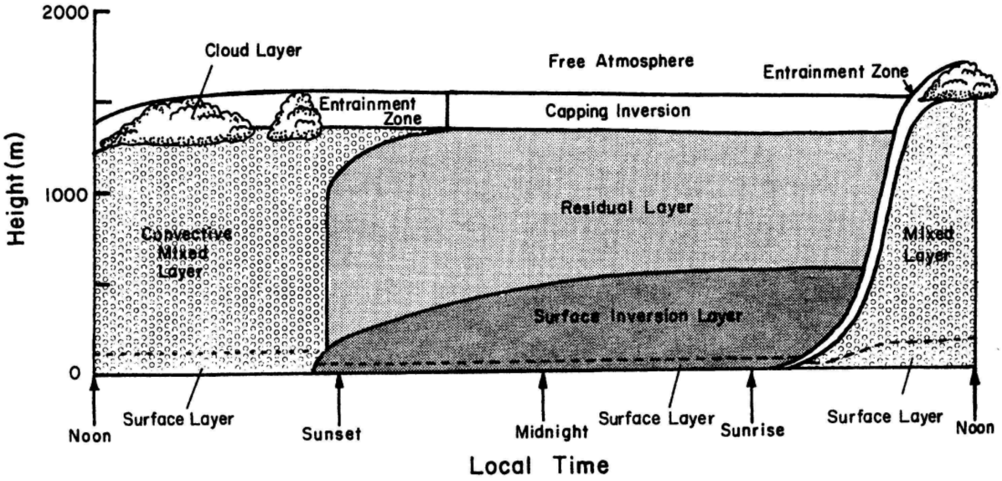

Figure 6: Structure of the convective boundary layer (CBL) according to Stull (1988). The structure of the different parts of the CBL coincides perfectly with the distribution of insect density during the day found by Contreras and Frasier (2008) shown in the following Figure 7.

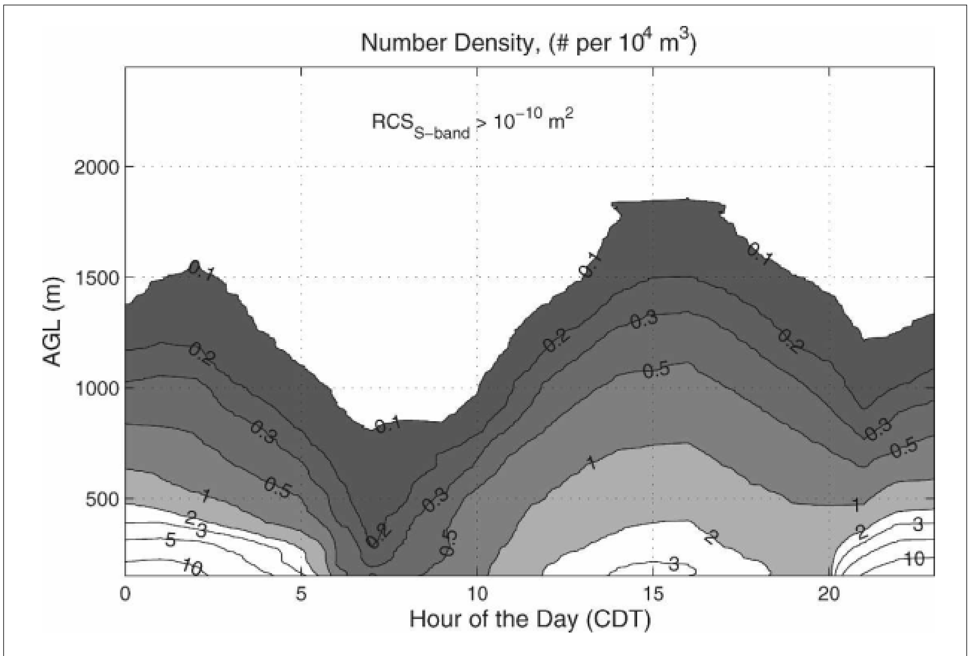

Figure 7: Diurnal composite of the number density of insects with S-band cross sections greater than 10^{10} m^2. The density is plotted as number per 10^4 m^3. Comment of the author: Copy taken from Contreras and Frasier (2008). Maximum flight density occurs during the night and to a lesser extent during daytime, with minima in between. Predominantly medium to large insects spotted. Sunrise approximately at 6:30, sunset approximately at 20:30 Central Day Time (CDT). The lower margin of the figure reaches down to approximately 150 meters AGL that is the lower detection boundary of the radar. Comparison of the structure of the CBL in Figure 6 with the motion patterns of flying insects in Figure 7 strongly supports the hypothesis that insects at night use stratified winds above the varying surface layer for migration.

In the 1990ies, when wind power development started to become commercial, most insects were commonly believed to stay below their so called flight boundary layer (FBL) that for most species reaches up to around 30 meters above ground level (Keuper 1993). The FBL was the argument that allowed wind power industry to proceed with its fast expansion without presenting any proof of tolerability with respect to flying insects, claiming that modern wind rotors will spin well above their natural habitat (Figure 4). It was also postulated that insects do not fly at high wind speeds, so insects would not be at risk during operation of wind farms at nominal power (Figure 8). Unfortunately, those assumptions are not universally valid for insect migration events.

5.3.2 The Insect Hypothesis

Here the phenomenon is attributed to the weather-dependent flying behaviour of insects. Figure 5.11 explains the mechanism in a diagram. It is assumed that the contamination of wind turbine blades increases only when insects are flying during turbine operation. Insects mostly fly when there is no rain, little wind and when it is not too cold, at temperatures above 10°C. If the turbine operates under these conditions, insects will increasingly contaminate the blade near the stagnation line. [Insects with a mass density much larger than air, follow a straight path when they crash on the frontal area of the airfoil near 0%*c*; at low wind speed (small angles of attack) the stagnation point is also near 0%*c*.] Here the flow is insensitive to contamination so that the power is not affected. [The flow speed near the stagnation point is low, so that the viscous shear is small, furthermore the negative pressure gradient beyond the stagnation point is stabilising the flow, which means that the flow will be almost independent of the contamination level near this point.] Above a certain wind speed, when insects rarely fly, the contamination remains constant. At high wind speed, the angle of attack along the blade is large and the suction peak has shifted to the contaminated area. [The flow speed in the suction peak is high, so that contamination causes high frictional drag in the boundary layer; moreover the positive pressure gradient beyond the suction peak destabilises the flow, which means that the flow will come to a standstill already at smaller angles of attack and thus will stall sooner.] Now the flow disturbance depends a great deal on the level of contamination, which shows itself as a decrease of the stall angle depending on the level of contamination. The smaller the stall angle, the lower the power level. This can also explain two or more power levels. The design level will be reached again when the blades are cleaned or when it rains during turbine operation.

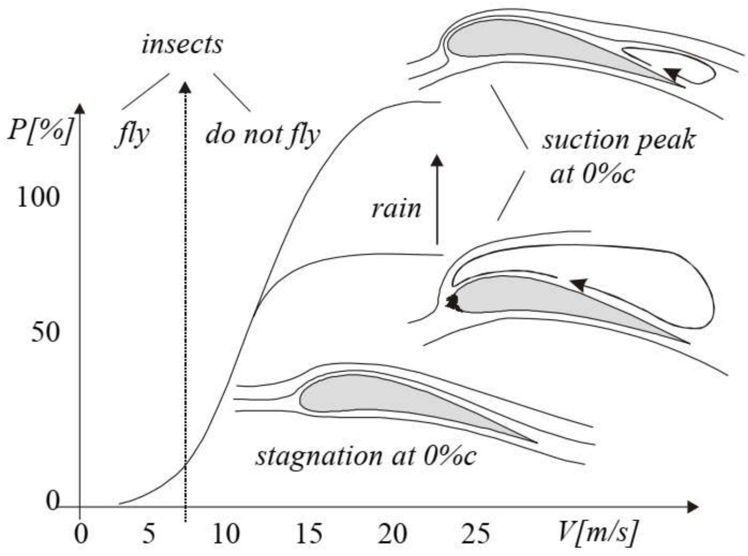

figure 5.11 *The Insect Hypothesis.*

Figure 8: The insect hypothesis of Corten (2001), pp. 107.

2.4 Species at risk

Being resilient and logical for diurnal motion patterns, the FBL concept may not be ubiquitously valid for mass migrating events and large swarms (Chapman et al. 2015). As an example, the Painted Lady (*Vanessa cardui*) together with most other butterflies was commonly thought to travel within its flight boundary layer until Stefanescu et al. (2013) discovered that “many long-distance migrants take advantage of favourable winds, moving downwind at high elevation (from some tens of metres from the ground to altitudes over 1000 m), pointing at strong similarities in the flight strategies used by *V. cardui* and other migrant Lepidoptera”.

Migrant butterflies like the Red Admiral (*Vanessa atalanta*) and many other large species like moths and grasshoppers were also supposed to migrate according to the FBL paradigm (e.g. Benvenuti et al. 1994 and many others). However, insects during migration behave differently, as has been shown by Mikkola (2003), Chapman (2004) and Chapman (2010), when observing and catching the above mentioned species and many others flying 100 and 200 meters high and higher (Table 1). The beetle *Omophlus lepturoides* and hundreds of its fellow specimen from Figure 3 (left) were also expected to stay low, but obviously did not. The supposed general validity of a flight boundary layer at around 30 meters above ground level may eventually not be valid for swarm migration.

Using different methods of assessment at different sites in Europe, insect species throughout all kind of taxa and sizes have been found flying high and making use of strong winds, ranging from aphids and drosophila with less than 0.5 milligram weight to butterflies like *V. atalanta* and moths like *N. pronuba* with up to 500 milligram weight. Cicadas like *J. pellucida,* beetles like *H. longitarsis* and the Painted Lady *C. septempunctata* as well as leaf- and grasshoppers like *A. argentarius* and *C. albomarginatus* have also been found travelling at 200 meters and more above ground. Table 1 gives some examples of general taxa and selected species found migrating in large swarms high in the sky.

Table 1: Taxa found flying considerably higher and faster than within their assumed flight boundary layer. For detailed lists of species please refer to Chapman et al. (2004) and Weidel (2008).

Aerial netting 200 m & vertical entom. radar, Chapman et al. 2004	Airplane trap at 100 to 1750 m, Weidel (2008)	Visual tracking (< 100 m), balloon aerial netting (200 m), rotor blade inspection (20 - 100 m) and vertical entomological radar tracking (150 - 1000^{+} m) of selected species in Southern, Central and Northern Europe
Hemiptera	Aphidina	*Vanessa atalanta* (Mikkola 2003)
Aphididae	Hymenoptera	*Omophlus lepturoides* (BladeCleaning 2017)
Diptera	Nematocera	*Vanessa cardui* (Stefanescu et al. 2013)
Hymenoptera	Brachycera	*Chorthippus albomarginatus* (Chapman et al. 2004)
Coleoptera	Coleoptera	*Athysanus argentarius* (Chapman et al. 2004)
Aranea	Psyllina	*Autographa gamma* (Chapman et al. 2010)
Thysanoptera	Thysanoptera	*Noctua pronuba* (Chapman et al. 2010)
Psocoptera	Araneida	*Colymbetes fuscus* (Chapman et al. 2004)
Neuroptera	Psocoptera	*Helophorus longitarsis* (Chapman et al. 2004)
Lepidoptera	Heteroptera	*Sigara distincta* (Chapman et al. 2004)
Orthoptera	Collembola	*Psychoda trinodulosa* (Chapman et al. 2004)
	Formicidae	*Javesella pellucida* (Reynolds et al. 2017b)
		Coccinella septempunctata (Jeffries et al. 2013)

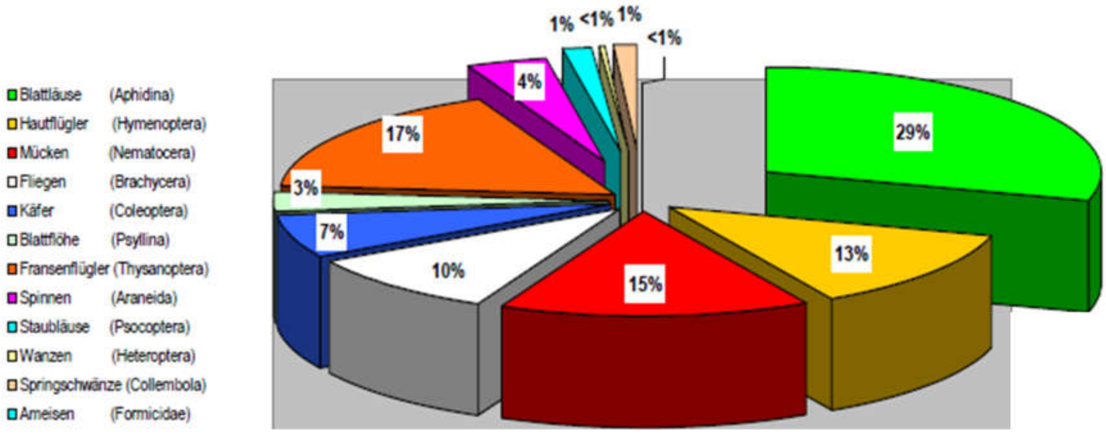

Figure 9: Distribution of insect taxa found up to 1750 m agl over Schleswig-Holstein, Germany between 1998 and 2004.

2.5 Critical periods in insect's life

The basic life cycle of holometabolic flying insects in Figure 10 shows four major stages of development (blue) and four transition periods in between (green). While the different stages can last from weeks to years, the transition periods, typically lasting only some hours or a few days, are rather short but represent a relatively critical, vulnerable period. Although life cycle is drafted as circle, it is in reality an up-winding spiral, with the change between levels from one generation to the following taking place between the adult insect stage and the egg stage. Migration usually takes place within this period with the purpose to find distant places to breed, to feed or to hibernate (Johnson 1969, Reynolds et al. 2017a).

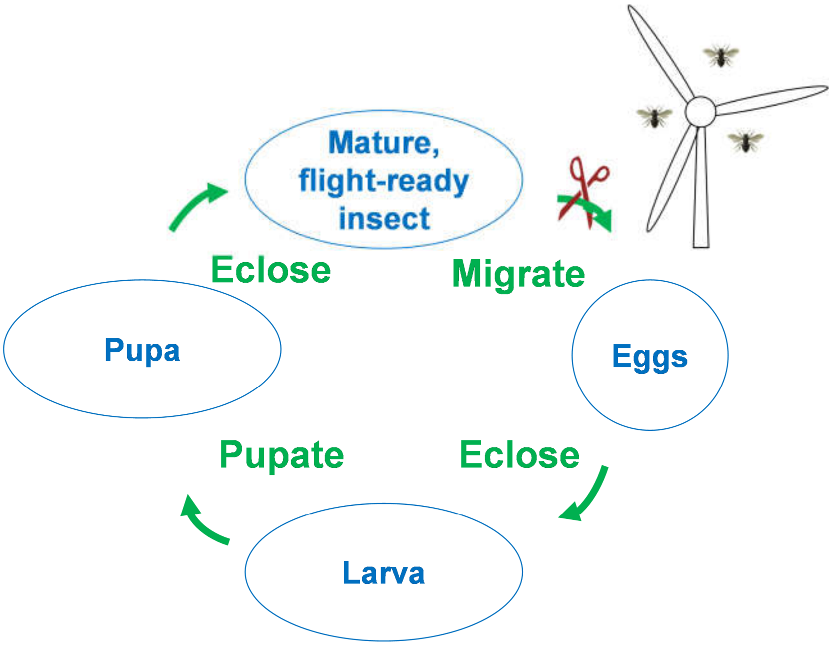

Figure 10: Life cycle of holometabolic flying insects (other developmental strategies include ametabolism and hemimetabolism): while the main stages of development (blue) can last from some weeks up to years, the transition periods from one stage to another (green) are relatively short.

It may be little persuasive that a unique and short event like migration could give room to significant losses of insect population. In principle one single female can lay hundreds of eggs, normally compensating for major losses caused by predators and other adverse agents. However, a strong lever action is applied on total insect population by killing a mature insect during migration just before breeding, as hundreds of potential successors from the next generation will as well be destroyed in doing so.

2.6 Additional hypotheses about insect attraction to wind farms

If migrating flying insects would be stochastically distributed in the air with densities varying vertically according to Figure 5, insect density and wind speed in the critical rotor layer would determine the number of insects that are carried by the wind through the rotors of wind farms. In fact, this simple model is used later in the study at hand, as conservative assumption. However, there are several factors that could further increase the number of insects in wind farms. Those factors are explained in the following in form of four additional hypotheses that however are neglected in the model assessment of jeopardized and damaged insect biomass presented later in this report:

2.6.1 Wind Speed Attraction Hypothesis

Hypothesis: Migrating insects select fast air streams just above the surface layer of the atmosphere in order to travel efficiently. Wind power developers do alike in order to optimize energy yield. This coincidence explains higher insect density in wind farms compared to calmer surroundings.

Evidence: As has been explained before, insects during migration actively seek high, strong winds for fast, long-distance displacement to new breeding grounds (Johnson 1969, Reynolds et al. 2017a). Such winds can be found just above the turbulent surface layer, particularly in regions with large, flat plains, on mountain ridges (Science News 2018) and on many coast lines. Wind-rich migration trails used by insects for millions of years are increasingly seamed by wind farms, as wind farms are selectively erected at sites with high average annual wind speed (Brower 2012).

2.6.2 Olfactory Attraction Hypothesis

Hypothesis: The smell of insect residues on rotor blades could act as olfactory lure. Hemolymph residues on rotor blades could attract scavengers and predators and misguide potential mates and swarm followers.

Evidence: Odor is one of the most important factors in insect behavior (Hansson 1999). Insects identify food, mates and predators by odor, with astounding range, spatial perception and high accuracy. Odors play a significant role in insect communication, swarm coordination and trail marking. Moreover, most insects are scavengers (Capinera 2010). Insect hemolymph residues are very attractive to them, because they provide the best blend of nutrients they need.

2.6.3 Acoustic Attraction Hypothesis

Hypothesis: a) Insects could be attracted to wind farms if the noise stemming from vibrations, rotating parts or the power generator inside the nacelle was similar to the noise generated by large swarms. b) If some insects would be attracted to wind turbines by any of the aforementioned factors, they could attract more insects by gravitational acoustic and visible attraction.

Evidence: Flying insects produce a big variety of humming sounds by beating their wings. Swarming species are known to be very sensitive to acoustic signals and individuals are thought to be attracted to swarms by sound. Acoustic interactions could be a basis for coordinating the large-scale collective behavior of swarms (Gorbonos et al. 2016). As an example, midges appear to be tightly bound to the swarm whilst at the same time weakly coupled inside it. Models based on Newtonian gravity do agree well with experimental observations and are biologically plausible since gravitational interactions have similitude with long-range acoustic and visual interactions. They correctly predict that individual attraction to the swarm center increases linearly with distance from the swarm center. There is evidence that this attraction increases with an individual's flight speed (Reynolds et al. 2017).

2.6.4 Visible Attraction Hypothesis

Hypothesis: Position lights and the color of the paint could attract flying insects to wind farms.

Evidence: The attraction of flying insects to different colors used for wind turbine structures has been assessed by Long et al. (2011). The common turbine paints 'pure white' (RAL 9010) and 'light grey' (RAL 7035) were among those found to attract significantly more insects than other colors tested. It is commonly known that light attracts flying insects, but the cause of attraction is not yet well understood and still controversially discussed. The degree of attraction of flying insects by the position lights of wind farms has not been assessed or quantified yet.

2.7 Missing proof of tolerability

There is no proof of tolerability of wind farms with respect to insects flying high in the sky during migration. Wildlife conservation rules in Germany only consider protection of species found at the construction site and regulate the vicinity of wind farms and protected or populated areas (UVPG 1990).

While birds and bats are usually taken into account in environmental impact assessment of wind farms (LUBW 2018), flying insects are commonly considered as insensitive in relation to wind power generation (MEE 2010).

However, there is no evidence that the impact of wind power generation on flying insect population is negligible. The quantity of affected insects can easily be underestimated by just visual appraisal of deposits on rotor blades, as only a small part of an insect's body will stick to the blade surface after an impact, while wind, rain and cleaning will regularly remove the major part of such remains.

Moreover, it should be noted that a loss of 75% of flying insect biomass in the past three decades as found by Hallmann et al. (2017) most likely reduces insect deposits on rotor blades observed today.

The fact that species mentioned in Table 1 migrate at a critical height of 20 to 220 meters above ground level puts into question a general tolerability of wind farms related to flying insects. It must be noticed that knowledge about taxa and amount of insects travelling high in the sky is yet fragmentary and not sufficient to exclude any flying insect species from the possibility of meeting a wind rotor during its mature life. According to Johnson (1969) it is not unlikely that most species do in fact migrate once in their life.

It also must be taken into account that insect migration takes place at national, international or intercontinental level and cannot be captured by analyzing local populations at wind farm sites.

The precaution principle explained in Article 20a of the German Basic Law postulates the implementation of prevention measures in case of significant potential damage, even if evidence is yet low (UBA 2015). Up to now, this principle has not been applied to possible interferences of wind parks and flying insects.

3. Model of jeopardized insect biomass

Not all migrating insects are jeopardized by wind farms, but only those that travel through the blade-swept, circular area of the spinning rotor of a wind turbine in operation. In order to calculate the amount of insect biomass (M_{insect}) that travels through the rotors of a wind park, the equations from Table 2 with the parameters from Table 3 can be used.

The amount of insects traversing a defined, vertical area like a wind rotor is directly proportional to insect density and wind speed, as formulated by equations 1a and 1b. If insects would be distributed evenly in the air and would only travel passively with the wind, in a specific time frame, fast wind would carry more insects through a specific rotor area than calm air with low speed. In addition to this effect that can be explained by simple physics, insects actively form swarms and add their own flight speed to wind speed for long-distance migration, increasing insect density within fast air streams compared to their calmer surroundings. For both reasons, wind farms that are usually placed at sites with high average wind speed will face particularly large amounts of migrating insects.

Table 2: Calculating air flux and amount of insects flying through a regional wind park. Presuming that flight through a rotor is only critical during operation, air and biomass flows during idle times must be subtracted from equations 2a and 5a, while 2b, 5b and 6b already consider idle times in the balance.

Theoretical Formulation	Eq.	Approximation	Eq.
$\mu_{insect,j}(t) = \delta_{insect,j}(t) \cdot v_{insect,j}(t)$	1a	$\mu_{insect} \cong \delta_{insect} \cdot v_{wind}$	1b
$m_{insect,j} = \int_{t=t1}^{t2} \mu_{insect,j}(t)dt$	2a	$m_{insect} \cong \mu_{insect} \cdot \Delta t$	2b
$M_{insect} = \sum_{j=1}^{n} m_{insect,j} \cdot A_j$	3a	$M_{insect} \cong m_{insect} \cdot A$ $\cong V_{wind} \cdot \delta_{insect}$	3b
$A = \sum_{j=1}^{n} A_j$	4a	$A \cong a_{average} \cdot P_{windpark}$	4b
$V_{wind,j} = A_j \cdot \int_{t=t1}^{t2} v_{wind,j}(t)dt$	5a	$V_{wind,j} \cong A_j \cdot v_{wind} \cdot \Delta t$	5b
$V_{wind} = \sum_{j=1}^{n} V_{wind,j}$	6a	$V_{wind} \cong A \cdot v_{wind} \cdot \Delta t$	6b

Table 3: Parameters used in the equations of Table 2: the upper section relates to the theoretical functions while the lower section gives approximations based on simplified average values.

Parameter	Unit	Definition	
Theoretical Formula			
$\mu_{insect,j}(t)$	kg/(m²s)	specific insect mass per area and time unit traversing the rotor of a wind turbine *j* as function of time	
$\delta_{insect,j}(t)$	kg/m³	insect mass density in the air that flows through the rotor of a wind turbine *j*	
$v_{insect,j}(t)$	m/s	ground speed (sum of active insect motion and wind speed)	
$m_{insect,j}$	kg/m²	time integral over the flying season of insect mass per unit area traversing the rotor of a wind turbine *j*	
A_j	m²	rotor area of a wind turbine *j*	
t_1	s	start of flying season (in Germany typically end of April)	
t_2	s	end of flying season (in Germany typically end of October)	
A	m²	total rotor area installed in a specific region	
M_{insect}	kg	insect mass traversing all rotors *j* = 1..*n* of a specific region in one season	
$V_{wind,j}$	m³	air volume flowing through a rotor *j* in one season	
V_{wind}	m³	air volume flowing through all rotors *j* = 1..*n* of a specific region in one season	
Approximation			**Examples**
μ_{insect}	kg/(m²s)	average specific insect mass traversing a rotor per area and time unit	$42 \cdot 10^{-9}$ kg/(m²s)
δ_{insect}	kg/m³	average insect density in the air during flying season	3 kg/km³ $\cdot 10^{-9}$ km³/m³
v_{wind}	m/s	average nominal design wind speed for full load operation	14 m/s
m_{insect}	kg/m²	average insect mass per area unit traversing a rotor during flying season	0.135 kg/m²
Δt	s	equivalent full load hours of operation during flying season	1000 h $\cdot$ 3600 s/h
$a_{average}$	m²/MW	average specific rotor area per unit capacity	2800 m²/MW
$P_{windpark}$	MW	installed capacity in a region (Germany)	56,000 MW (Table 4)
A	m²	approximate total rotor area installed in a specific region (Germany)	$158 \cdot 10^{6}$ m² (Table 4)
M_{insect}	kg	approximate insect mass traversing the total rotor area of a specific region (Germany) in one season	8,000 t - 24,000 t (Table 4)
V_{wind}	m³	air volume flowing during operation through all rotors of a specific region (Germany) within one season	$8 \cdot 10^{6}$ km³ $\cdot 10^{9}$ m³/km³ (Table 4)

Solving equations 1a, 2a and 3a would require a continuous monitoring of density and ground speed of insects traversing the rotor of each German wind turbine during the whole insect flying season that lasts from end of April to end of October, which would hardly be possible to achieve. A more practical approach would be based on monitoring a limited number of representative wind farms and trying to extrapolate results to the total German wind farm inventory.

Whether such a demanding and expensive enterprise would be worthwhile is certainly related to the amount of insect biomass that could be under risk every year, which is equal to the mass of insects that is carried through the rotors during operation. Prior theoretical assessment can shed light to that question.

Fortunately, some limited empirical information on average insect density in the atmospheric boundary layer and on typical operation wind speeds of the German wind park is available that allow a simplified calculation of related volume and mass flows. Thus, in order to obtain a conservative estimate of the possible order of magnitude of the mass of insects carried by the wind through the German wind park during operation throughout one season, the approximations 1b, 2b and 3b or alternatively 6b and 3b can be used. In this approximation, only the physical effect of higher wind speed bringing higher amounts of insects to wind farms is considered, while an active selection and accumulation of insects in fast air streams according to the hypotheses presented above is neglected.

To complement this approach, the total rotor area of the German wind park can be estimated from equation 4b, considering that the rated wind power capacity installed in Germany since 1988 is $P_{Windpark}$ = 56,356 MW (Figure 11) and the average specific rotor area per rated power unit is approximately $a_{average} \approx$ 2,800 m²/MW. Equation 4b yields a total rotor area of about 158 million square meters that has been installed in Germany in the past three decades at a height between 20 and 220 meters above ground (Table 4).

The amount of insect biomass that is potentially affected by wind farms is limited to those insects that are carried through the rotors during operation between end of April and end of October, which is the warm season with a significant content of aerial plankton in the atmospheric boundary layer. Operation time at nominal full load during the warm season can be assessed from German wind park statistics and ranges in the order of Δt = 1000 equivalent full load operating hours (Figure 12). The average nominal wind speed related to those full load hours is assumed to be v_{wind} = 14 m/s (WTM 2018), neglecting active motion of insects and wind speeds higher than nominal, as conservative assumptions. For the year 2017, equation 6b yields an air flux of 8 million cubic kilometers through the German wind park during operation in the warm season, which is equivalent to more than ten times the size of the atmospheric boundary layer over Germany up to two kilometers above ground (Table 4).

Weidel (2008) used traps mounted on an airplane in order to determine the species and number of insects that travel up to 1750 meters above ground. Between the years 1998 and 2004 he found an average density of insect biomass of δ_{insect} = 3 kg/km³ in the convective daytime boundary layer over the Federal State of Schleswig Holstein in Northern Germany.

Equations and parameters explained before can be used to build a model of potentially affected insect biomass that has traveled through the German wind park in the past decades. However, according to the findings of Hallmann et al. (2017) of a loss of 75% in 27 years, density of flying insects in the atmosphere cannot be assumed to remain constant with time, but must decrease accordingly. Furthermore, as has been explained before, insects are not uniformly distributed within the boundary layer, which requires further corrections for model calculation (Johnson 1957).

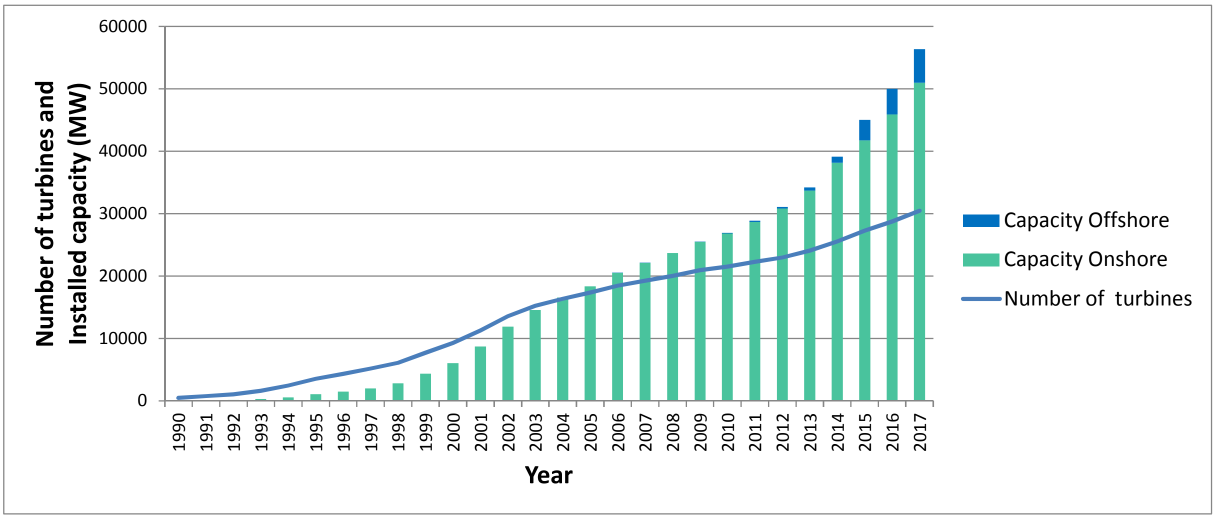

Figure 11: Development of wind power capacity installed in Germany since 1990 (Rohrig et al. 2018)

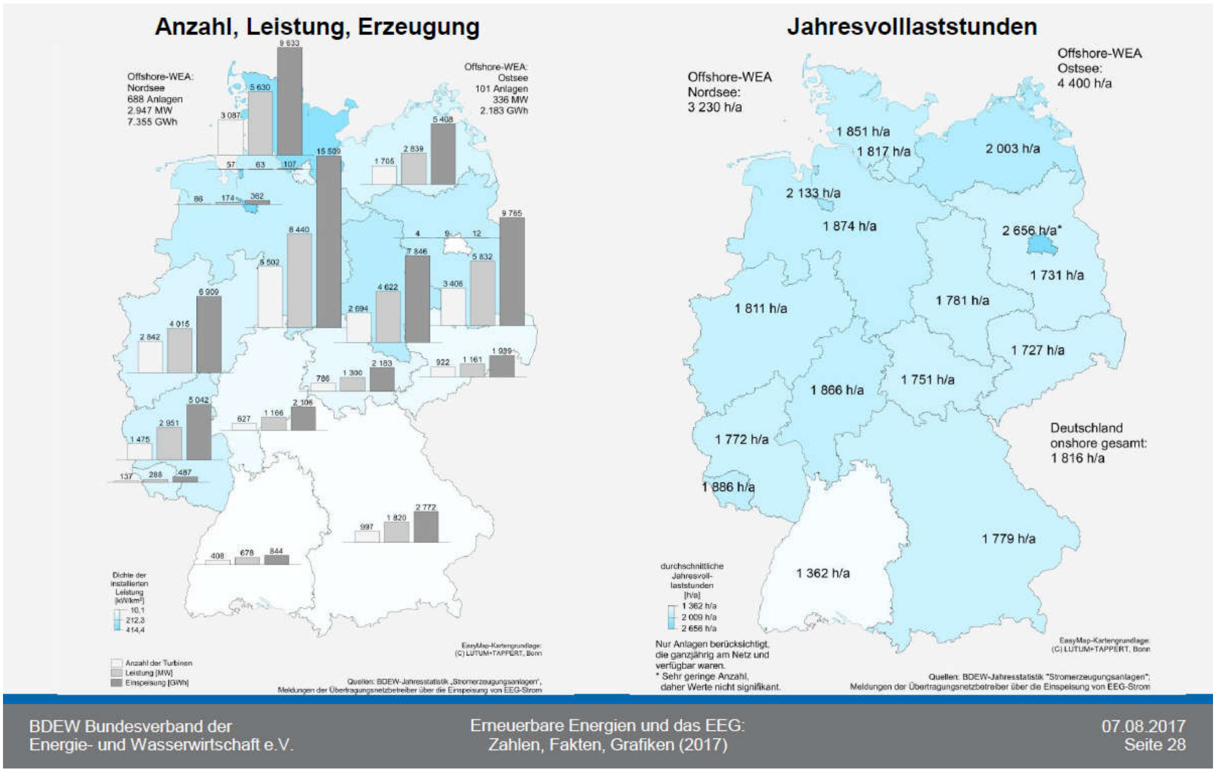

Figure 12: Number, capacity, generation and full load hours of wind turbines installed in Germany in 2017 (BDEW 2017).

In order to get an estimate of potentially affected insect biomass as function of time, three cases based on different assumptions about the distribution of insect density have been analyzed (Table 4):

a) Constant average insect density in the total atmospheric boundary layer up to 1750 meter above ground of 3 kg/km³ as found by Weidel (2008) between 1998 and 2004, neglecting losses before and after that and also neglecting non-uniform vertical distribution of insects in the boundary layer. This assumption results in an amount of jeopardized insect biomass that steadily increases since 1990 in line with installed capacity and air flux of German wind farms. A maximum 24,000 tons of insects would be under risk today during the flying season, and cumulated 209,000 tons would have been at risk in the past (Table 4). As insect density at rotor height can be expected to be significantly higher than the average over the total height of the atmospheric boundary layer, this model is not used further.

b) Constant density as before, but assuming three times higher than average density in the lower part of the boundary layer at critical rotor height according to Figure 5. This assumption conservatively follows Johnson (1957) and Drake (1984) that in many cases found three- to fourfold higher than average concentrations at that height. The approximation roughly takes into account vertical distribution of flying insects in the atmosphere. The result of this assumption is similar to the former one but yields higher potentially affected biomass of more than 72,000 tons in 2017 (Figure 13, red solid line). In this case, cumulated 626,000 tons would have been at risk in the past decades.

c) Decreasing insect density in line with the findings of Hallmann et al. (2017) and based on the average value of 9 kg/km³ at critical rotor height, taking 2003 as reference year, with a linear backward gradient of +2.5%/a until 1990 and a forward gradient of -5%/a until 2017, following the trend in Figure 2. This model takes into account non-uniform vertical distribution of insect biomass and insect losses over the past decades. As a result, high air flux through a large wind park in recent years combines with increasingly low average insect density, resulting in about 24,000 tons per year of potentially affected biomass that would have remained almost constant for the past 15 years in spite of a dramatic reduction of insect population and a likewise dramatic expansion of wind power capacity in that period (Figure 13, black solid line). Under this assumption, a cumulated insect biomass of 392,000 tons would have been at risk during the past 30 years.

The assumed evolution of insect density in model case c) takes into account a steeper decline of flying insects after 2003 according to Figure 2. Comparing the curves in Figure 13 shows that after the year 2003 impact on flying insects is limited by decreasing insect density (curve c) and not any more by the size of the German wind park as before that year. Wind power capacity installed after 2003 would easily allow for much higher impact if insect density would remain constant (curve b).

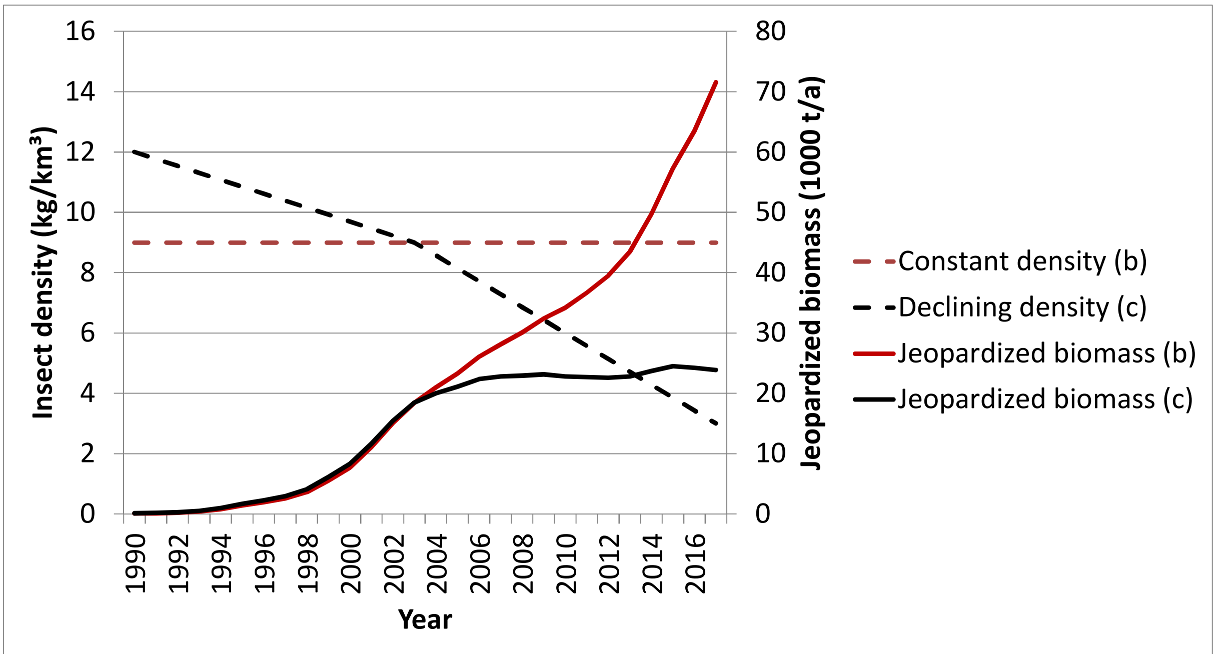

Figure 13: Model of flying insect biomass as function of time traversing the wind rotors of the German wind park based on different assumptions according to Table 4. If insect density would have remained constant as in model case b), much more insects would have been jeopardized by wind farms after 2003 than in model case c) with declining insect density.

Table 4: Model of insect biomass flying through wind rotors in Germany since 1990, taking as reference a) average insect density of 3 kg/km³ in the total atmospheric boundary layer (ABL) according to Weidel (2008), b) insect density of 9 kg/km³ at rotor height according to Figure 5 and c) decreasing density at rotor height in line with the findings of Hallmann et al. (2017).

				a) Average Density in the Total ABL		**b) Constant Density at Rotor Height**		**c) Decreasing Density at Rotor Height**	
Year	Installed Capacity	Rotor Area	Saisonal Flow	Insect density (a)	Jeopardized biomass (a)	Insect density (b)	Jeopardized biomass (b)	Insect density (c)	Jeopardized biomass (c)
	$P_{windpark}$	A	V_{wind}	δ_{insect}	M_{insect}	δ_{insect}	M_{insect}	δ_{insect}	M_{insect}
	MW	10^6 m²	10^6 km³	kg/km³	1000 t	kg/km³	1000 t	kg/km³	1000 t
1990	63	0.2	0.0	3.00	0.0	9.00	0.1	12.00	0.1
1991	105	0.3	0.0	3.00	0.0	9.00	0.1	11.77	0.2
1992	175	0.5	0.0	3.00	0.1	9.00	0.2	11.54	0.3
1993	319	0.9	0.0	3.00	0.1	9.00	0.4	11.31	0.5
1994	612	1.7	0.1	3.00	0.3	9.00	0.8	11.08	1.0
1995	1,092	3.1	0.2	3.00	0.5	9.00	1.4	10.85	1.7
1996	1,525	4.3	0.2	3.00	0.6	9.00	1.9	10.62	2.3
1997	2,037	5.7	0.3	3.00	0.9	9.00	2.6	10.38	3.0
1998	2,849	8.0	0.4	3.00	1.2	9.00	3.6	10.15	4.1
1999	4,352	12.2	0.6	3.00	1.8	9.00	5.5	9.92	6.1
2000	6,069	17.0	0.9	3.00	2.6	9.00	7.7	9.69	8.3
2001	8,710	24.4	1.2	3.00	3.7	9.00	11.1	9.46	11.6
2002	11,873	33.2	1.7	3.00	5.0	9.00	15.1	9.23	15.5
2003	14,546	40.7	2.1	3.00	6.2	9.00	18.5	9.00	18.5
2004	16,534	46.3	2.3	3.00	7.0	9.00	21.0	8.57	20.0
2005	18,346	51.4	2.6	3.00	7.8	9.00	23.3	8.14	21.1
2006	20,527	57.5	2.9	3.00	8.7	9.00	26.1	7.71	22.3
2007	22,144	62.0	3.1	3.00	9.4	9.00	28.1	7.29	22.8
2008	23,704	66.4	3.3	3.00	10.0	9.00	30.1	6.86	22.9
2009	25,508	71.4	3.6	3.00	10.8	9.00	32.4	6.43	23.1
2010	26,926	75.4	3.8	3.00	11.4	9.00	34.2	6.00	22.8
2011	28,873	80.8	4.1	3.00	12.2	9.00	36.7	5.57	22.7
2012	31,095	87.1	4.4	3.00	13.2	9.00	39.5	5.14	22.6
2013	34,227	95.8	4.8	3.00	14.5	9.00	43.5	4.71	22.8
2014	39,153	109.6	5.5	3.00	16.6	9.00	49.7	4.29	23.7
2015	45,043	126.1	6.4	3.00	19.1	9.00	57.2	3.86	24.5
2016	50,011	140.0	7.1	3.00	21.2	9.00	63.5	3.43	24.2
2017	56,356	157.8	8.0	3.00	23.9	9.00	71.6	3.00	23.9
Cumulated Biomass (1990 - 2017):					209		626		392

4. Model of damaged insect biomass

Not all flying insects that are carried by the wind through a rotor are endangered. Looking at a rotor from the front, there is a lot of space left free (Figure 4). In principle, flying with the air, no insect would ever hit a blade, as the air always flows around the blades and not against them. However, due to the mass inertia of their body, insects can be separated from the flow if the air suddenly changes direction under the influence of an approaching rotor blade (Figure 14).

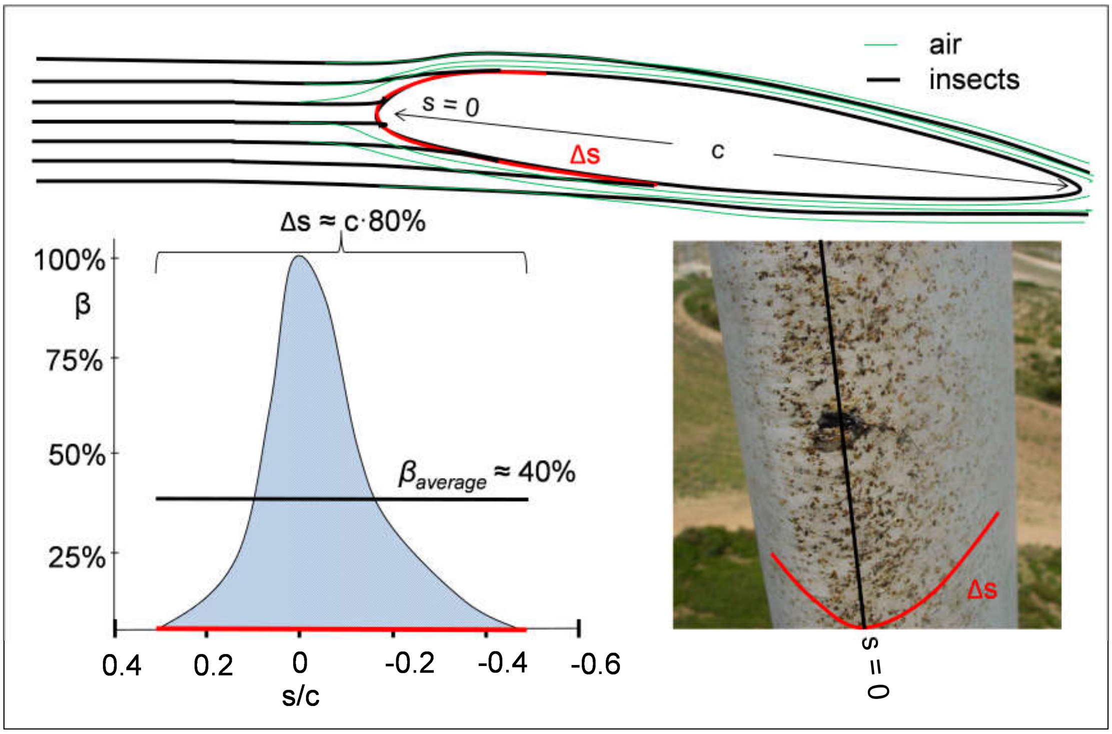

Figure 14: Approximation of the effective impact area of a rotor blade following the analysis of Wilcox & White (2016). Top: insect trajectories on an airfoil (wrap distance s, leading edge at s=0, chord length c, impact length Δs (red line). Left: collection efficiency β as function of distance (s/c) from the leading edge (s=0) and the average integral collection efficiency $\beta_{average}$ assumed in the model. Variability depending on pitch angle and insect inertia is neglected. Right: Photo of insect residues (refer to Figure 3) explaining leading edge and impact length of a rotor blade as used in the model.

The portion of insects that may hit a blade when flying through a rotor can be estimated from equation 7. This equation is derived from theoretical and empirical analysis of insect deposits on rotor blades by Wilcox & White (2016) and Wilcox et al. (2017). According to them, the mass of insect impingement per area and time unit is proportional to the insect density in the air, to the effective wind speed combining freestream and blade rotational velocities and to the average integral collection efficiency of the blade surface. Although Wilcox et al. only used their findings for modelling insect deposits on rotor blades their model can also be used for estimating losses of insects flying through rotors, as both analyses are related to the density of insects in the air. Adapting this relation to our purposes yields:

$$\rho_{damage} = \rho_{surface} \cdot \rho_{impact} \cdot \beta_{average} \cdot \frac{v_{eff,model}}{v_{wind}} \qquad \text{Equation 7}$$

With the following parameters (assumed as average representative values for the total wind park):

$\rho_{surface} = \frac{A_{Blades}}{A_{Rotor}} = 5\%$ average ratio of the projected surface of all blades (A_{Blades}) to the total circular (swept) rotor area (A_{Rotor}),

$A_{Blades} = A_{Blade} \cdot n_{Blades}$ average total blade area of a rotor with n_{Blades} blades,

$\rho_{impact} = \frac{\Delta s \cdot L}{c \cdot L} = 80\%$		average ratio of impact surface on both sides of the blade $\Delta s \cdot L$ to the projected blade surface $c \cdot L$, assuming a constant ratio over the whole blade length L,
$\beta_{average}$	= 40%	average integral collection efficiency of the impact surface,
$v_{eff,model}$	= 45 m/s	average effective wind speed (ranges from up to 80 m/s at the tip to less than 10 m/s at the nacelle),
v_{wind}	= 14 m/s	average nominal wind speed used also for calculating M_{Insect}.

Variations depending on blade angle and insect size are neglected or rather assumed to be included in the average values. For the definitions of $v_{\text{eff,model}}$ and A_{Blade} please refer to Figure 15:

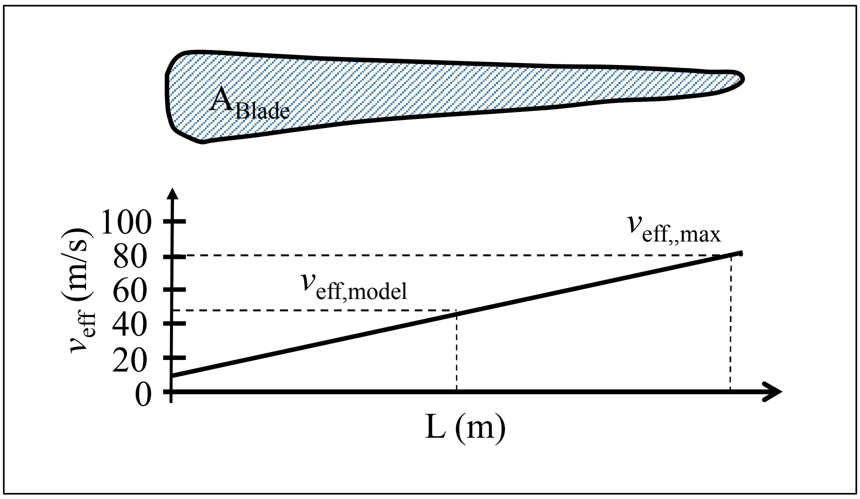

Figure 15: Illustration of the definition of the projected area of one rotor blade and of the average effective speed of the rotor blade versus the surrounding wind used in the model.

Equation 7 yields an average portion of about 5% of insects damaged when travelling through wind rotors in operation, which means that about 95% will pass unharmed. The results concerning impact surface, collection efficiency, blade speed and impingement rates coincide with the findings of Fiore & Selig (2015) who also provide a theoretical basis for calculating insect impingement on airfoils. It must be considered that our approximation is very simplified and rather conservative, assuming among other simplifications nominal operation wind speed as general reference for the calculations. This means that damage occurring at lower and higher than nominal wind speeds is assumed to be included in the calculation (Table 6).

Finally, equation 8 can be used for a rough estimate of the order of magnitude of possible damage:

$$M_{damage} = \rho_{damage} \cdot M_{insect} \qquad \text{Equation 8}$$

Figure 16 and Table 5 reveal that in model case b) with a constant insect density at rotor level of 9 kg/km³, losses would increase proportionally to wind power capacity installed since 1990, and reach a maximum 3,600 tons in 2017. In model case c) insect losses would stagnate after 2003 at around 1,200 tons per year, due to an increasing lack of available insects in the air. The modelled losses remain approximately constant after 2003, because insect biomass after that year decreased approximately at the same rate as wind power capacity increased at around 5%/a, as has been shown by Hallmann et al. (2017) for insect biomass and by Rohrig et al. (2018) for wind power.

Table 5: Model of insect biomass damaged in German wind farms since 1990, taking as reference a) constant average insect density of 3 kg/km³ in the total atmospheric boundary layer according to Weidel (2008), b) insect density of 9 kg/km³ at rotor height according to Figure 5, remaining unchanged over the years, and c) since 1990 decreasing density at rotor height in line with the findings of Hallmann et al. (2017).

				a) Average Density in the Total ABL		b) Constant Density at Rotor Height		c) Decreasing Density at Rotor Height	
Year	Installed Capacity	Rotor Area	Saisonal Flow	Insect density (a)	Damaged biomass (a)	Insect density (b)	Damaged biomass (b)	Insect density (c)	Damaged biomass (c)
	$P_{windpark}$	A	V_{wind}	δ_{insect}	M_{damage}	δ_{insect}	M_{damage}	δ_{insect}	M_{damage}
	MW	10^6 m²	10^6 km³	kg/km³	1000 t	kg/km³	1000 t	kg/km³	1000 t
1990	63	0.2	0.0	3.00	0.0	9.00	0.0	12.00	0.0
1991	105	0.3	0.0	3.00	0.0	9.00	0.0	11.77	0.0
1992	175	0.5	0.0	3.00	0.0	9.00	0.0	11.54	0.0
1993	319	0.9	0.0	3.00	0.0	9.00	0.0	11.31	0.0
1994	612	1.7	0.1	3.00	0.0	9.00	0.0	11.08	0.0
1995	1,092	3.1	0.2	3.00	0.0	9.00	0.1	10.85	0.1
1996	1,525	4.3	0.2	3.00	0.0	9.00	0.1	10.62	0.1
1997	2,037	5.7	0.3	3.00	0.0	9.00	0.1	10.38	0.1
1998	2,849	8.0	0.4	3.00	0.1	9.00	0.2	10.15	0.2
1999	4,352	12.2	0.6	3.00	0.1	9.00	0.3	9.92	0.3
2000	6,069	17.0	0.9	3.00	0.1	9.00	0.4	9.69	0.4
2001	8,710	24.4	1.2	3.00	0.2	9.00	0.6	9.46	0.6
2002	11,873	33.2	1.7	3.00	0.3	9.00	0.8	9.23	0.8
2003	14,546	40.7	2.1	3.00	0.3	9.00	0.9	9.00	0.9
2004	16,534	46.3	2.3	3.00	0.3	9.00	1.0	8.57	1.0
2005	18,346	51.4	2.6	3.00	0.4	9.00	1.2	8.14	1.1
2006	20,527	57.5	2.9	3.00	0.4	9.00	1.3	7.71	1.1
2007	22,144	62.0	3.1	3.00	0.5	9.00	1.4	7.29	1.1
2008	23,704	66.4	3.3	3.00	0.5	9.00	1.5	6.86	1.1
2009	25,508	71.4	3.6	3.00	0.5	9.00	1.6	6.43	1.2
2010	26,926	75.4	3.8	3.00	0.6	9.00	1.7	6.00	1.1
2011	28,873	80.8	4.1	3.00	0.6	9.00	1.8	5.57	1.1
2012	31,095	87.1	4.4	3.00	0.7	9.00	2.0	5.14	1.1
2013	34,227	95.8	4.8	3.00	0.7	9.00	2.2	4.71	1.1
2014	39,153	109.6	5.5	3.00	0.8	9.00	2.5	4.29	1.2
2015	45,043	126.1	6.4	3.00	1.0	9.00	2.9	3.86	1.2
2016	50,011	140.0	7.1	3.00	1.1	9.00	3.2	3.43	1.2
2017	56,356	157.8	8.0	3.00	1.2	9.00	3.6	3.00	1.2
Cumulated Biomass (1990 - 2017):					10		31		20

A loss of 1,200 tons of flying insect biomass destroyed every year (model case c) is equivalent to an order of magnitude of 2.4 billion moths of the species *N. pronuba* with a weight around 500 milligram each or 2.4 trillion aphids with around 0.5 milligram lost every year since over a decade.

Assuming an average weight of around one milligram per insect like Hu et al. (2016) for the total migrating insect population leads to a loss of about 1.2 trillion insects of different species per year, which is a first rough but conservative estimate of the impact of wind farms on flying insects in Germany since more than a decade. In this context it should be noted that impact is not limited to local populations, but includes species like the Ladybird beetle (*C. septempunctata*) and the Painted Lady butterfly (*V. cardui*) that travel hundreds and even thousands of kilometers distance through Europe and Africa during their regular migration events (Jeffries et al. 2013, Stefanescu at al. 2013).

Comprehensive work on insect migration has been done by Hu et al. (2016) indicating an annual average amount of 3.37 trillion insects (3,200 tons of biomass) migrating over an area of 70,000 km² in Southern England between the years 2000 and 2009 (Figure 17). Their results cannot be compared directly to the 1.2 trillion lost insects (1,200 tons) calculated here, because the total amount of flying insects in Southern England cannot be easily extrapolated to another region. The comparison only shows that losses of a trillion per year certainly have a relevant order of magnitude.

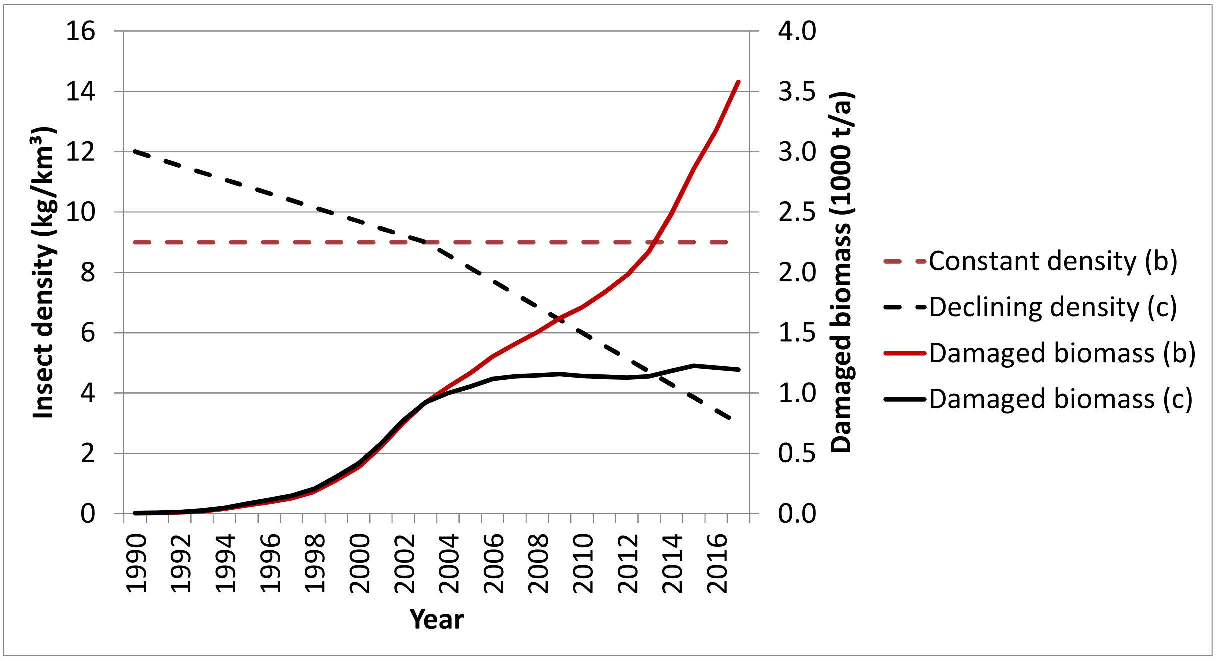

Figure 16: Insect density and damaged biomass resulting from model cases b) with constant density and c) with decreasing density since 1990. While case b) reveals a damage increasing directly proportional to the expansion of wind power capacity, case c) shows a stagnation after 2003, which is due to an increasing lack of insect biomass in the air.

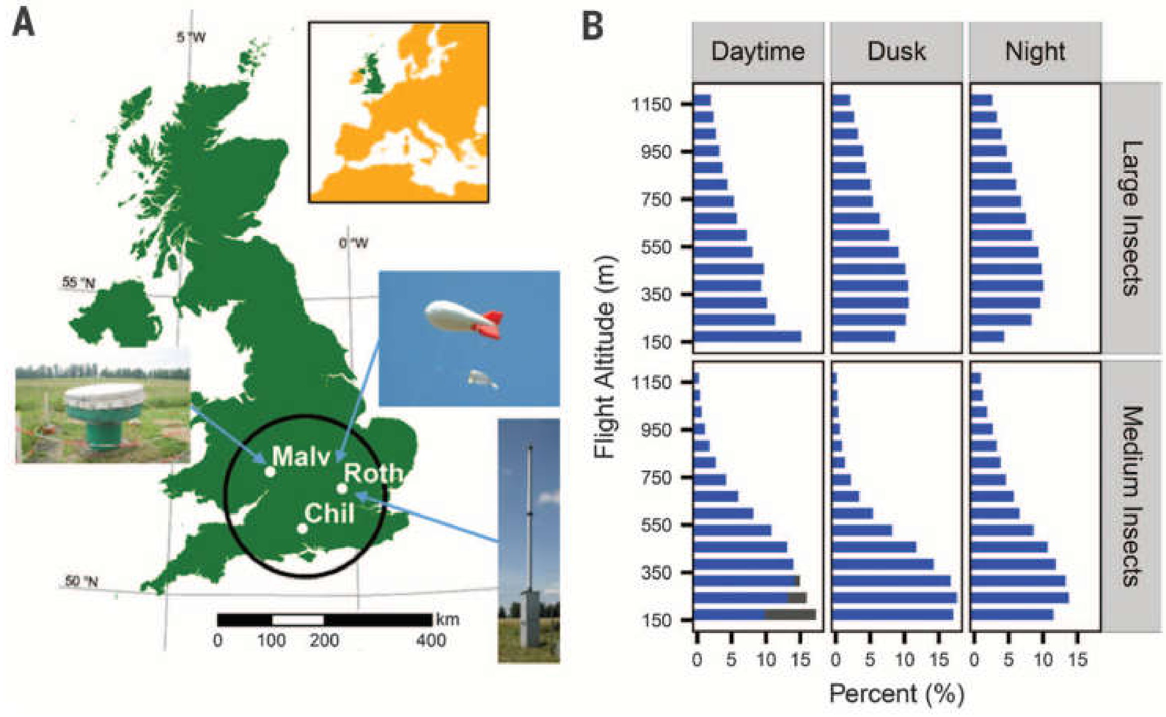

Figure 17: Monitoring migration intensity above the southern United Kingdom. (A) The intensity and direction of high-altitude insect migration through the atmosphere 150 to 1200 m above ground level (AGL) was measured over a 70,000-km² region of the southern United Kingdom (black circle) under continual surveillance from vertical-looking radars (VLR, left inset) at three locations (white dots); the aerial insect fauna were sampled by balloon supported aerial netting at 200 m AGL (center-right inset) and 12-m-high suction traps (bottom-right inset). (B) Vertical profiles of larger insect (>10 mg) migration intensity over the sampling range of the VLRs. Copy taken from Hu et al. (2016).

Table 6: Factors considered and factors neglected in the model.

Model assumptions taken into account	Factors neglected in the model
Average insect density measured in the year 2003 in the boundary layer over Schleswig-Holstein up to 2.000 meters above ground level of 3 kg/km³ assumed to be valid for total Germany.	Selection of high, fast air streams by migrating flying insects and further attraction hypotheses that may lead to a higher than average concentration of insects in wind farms.
Approximately logarithmic vertical distribution of insect density up to 2.000 m above ground level, assuming a density of 9 kg/km³ at critical rotor height in the year 2003.	Swarm behavior of different insect species during day- and nighttime. Elevation and settling at dusk and dawn leading to a transit through the critical rotor height two times per day during migration.
Operation of all rotors at nominal 14 m/s wind speed for 1.000 equivalent full load operating hours per year during the warm season (ca. 7 months) for the calculation of airflow through the German wind park of 8 million km³ in the year 2017.	Higher number of effective operating hours of wind farms at other than nominal wind speeds, and insect speed relative to the surrounding air lead to higher impact risk on rotor blades.
Average effective impact surface of ca. 32% (80% impact surface x 40% collection efficiency) of the projected blade area responsible for insect damage, calculated from theoretical and empirical models quantifying dirt accumulation on rotor blades.	Impact length and collection efficiency of rotor blades vary with varying inertia of insects of different size: impact probability is much higher for large and heavy insects than for small ones.
Direct impact on rotor blades with visible residues with an average probability of 5% of the total insect biomass traversing the circular blade-swept rotor area.	Barotrauma by flying through the low pressure area at the suction side of the blades, and damage by partial impact (e.g. at mouthparts, antenna, eyes, wings, legs, genitalia, etc.) without visible residues.

5. Discussion of results

The work at hand is based on scientific literature available since the middle of the past century and recent findings about insect migration, and literature about insect impingement on wind rotor blades available since 1990 and more recently. The models used, quantifying air flux through wind farms and potential impingement on rotor blades are simple but robust. Evidence on insect density in the atmospheric boundary layer and on the total amount of insects travelling over a specific region is fragmentary, making it difficult to quantify losses in relation to the total affected population.

The findings of this study are based on average insect density that has been assessed between 1998 and 2004 in the Federal State of Schleswig Holstein, Germany, which is the only source of such information found in Germany. Insect losses during the past three decades certainly had an impact on insect density in the air, but it is not known how exactly density has changed. Assuming a linear correlation of insect losses of insects near the ground found by Hallmann et al. (2017) and average insect density in the air found by Weidel (2008) as shown in Table 4 and Table 5 is a simple approach, but there might be more complex relations involved.

An average insect density of 3 kg/km³ from Weidel (2008) used here as reference for our calculations is related to the daytime convective boundary layer and does not include night time situations. It is not known how average insect density would change when taking into account night time insect migration, especially concerning larger species, which could affect the results (see e.g. Figure 7).

The resulting number of around one thousand billion damaged insects per year or about 5 billion per day during the warm season (200 days) between April and October – besides of being a rough estimate based on fragmentary and limited information – cannot be related directly to the amount of total flying insect population crossing over Germany, which is unknown and still requires further investigation. It also cannot be related to other impacts that have not been quantified either.

6. First ideas for loss assessment and mitigation

A simple and reliable, but up to now unexploited way of identifying insects within the critical rotor layer is DNA barcoding & meta-barcoding (Geiger et al. 2016). Both methods rely on a short DNA sequence in an organism's DNA, which is specific for each species. Via the comparison of DNA sequences from unknown samples with DNA barcodes already available in public reference databases, an unknown organism can be assigned to a species (Herbert et al. 2003). Wind farms carry all information that is needed to identify any species that flies at critical height, by analyzing the DNA barcodes contained in the deposits that are regularly found on rotor blades. This will not only provide valuable information about insect behavior in that layer, but will at the same time reveal what species in addition to those mentioned in Table 1 are under risk of being jeopardized by wind farms.

Insect swarm detection by Radar and Lidar and an according control of the blades is an obvious preventive measure. Insects and other aerosols are already used today by Lidar and Radar systems in order to analyze approaching wind fields for optimization of wind farm operation (Harris et al. 2006, WindForS 2018). Similar equipment is developed and applied for bird and bat detection (KNE 2018).

Another important measure of prevention is the identification and monitoring of environmental conditions that are favorable for swarm formation and migration. Monitoring of swarm events at wind farm sites as part of the environmental impact assessment procedures and during operation has already been proposed thirty years ago by Böttger (1990), but was discarded due to the erroneous assumptions on insect behavior and insect habitat limitations mentioned before.

7. Conclusions

The study aims at raising awareness about wind power generation being one of the possible causes of insect biomass lost in several nature reserve areas in Germany. The order of magnitude of insect losses caused by wind power generation has been quantified theoretically for the first time. Losses caused by insecticides, herbicides, monocultures, human transport, light contamination, climate change and urbanization have not been quantified yet. For this reason, it is impossible to say to what extent the different impacts are responsible for insect decline, or which impact is the most harmful one. In any case, all impacts on insect population probably add to each other.

The amount of jeopardized insect biomass of several thousand tons per year derived from simple mass balance under conservative assumptions, the large number of species throughout all taxa together with the high insect densities found at critical rotor heights, and visible evidence of an uncounted number of insects being killed by wind rotor blades since more than thirty years, call for in-depth assessment of all possible interactions involved and for empirical verification of the theoretical estimate of about a trillion per year lost in German wind farms.

A particularly worrying finding of the study is that the German wind park would damage much more insects if they were available, as can be seen by comparing model cases b) and c). This means that if insect population in Germany would recover for any reason and return to a density at rotor height of 9 kg/km³ as in the beginning of the century around 2003, wind power would counteract such effort on a scale of 3,600 tons of damaged insects per year. Seen from another perspective, the German wind park would have a significant mitigation potential with respect to insect losses of up to 3,600 tons annually, which would be a significant contribution to wildlife conservation if put into practice.

Identifying concerned taxa by DNA meta-barcoding insect deposits on rotor blades and empirically quantifying losses by comprehensive observation of wind farms are urgently needed next steps towards greater awareness and understanding of the problem, immediately followed by the development and installation of effective counter measures.

Acknowledgements

The author thanks all involved scientists from the interdisciplinary group that helped to realize the investigation, from the Zoological Institute of the University of Hohenheim, the Institute of Functional Morphology and Biomechanics, Kiel University, the Zoological Research Museum Alexander Koenig, the Entomological Society of Krefeld, the Institute of Atmospheric Physics as well as the Institute of Engineering Thermodynamics of the German Aerospace Center, and the Fraunhofer Institute for Energy Economics and Energy System Technology, for their rigorous review and kind advise.

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