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Towards an improved wind speed scale vs. damage description adapted for Central Europe

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Abstract

We propose an updated verbal wind speed scale description adapted for Central Europe considering wind impact to buildings as well as to vegetation. It is motivated by the need of a broadly applicable, accurate and consistent tornado or downburst intensity rating system based on a standardised wind speed scale for the purpose of climatological homogeneity. The description comprises building and vegetation damage characteristics occurring with the various classes of the Fujita- and T-scales and is supplemented by photographs of typical damage. For practical application, an ensemble-based use of a decision matrix for specific building structures and vegetation types is suggested.

Keywords: Wind speed scale; Property damage; Vegetation damage; Loss ratio; Fujita scale; T-scale; EF-scale; E-scale

1 Introduction

Determination of wind speeds in severe convective weather phenomena like tornadoes or downbursts is a difficult task, because of their very localized and short-lived nature and, thus, they are usually not recorded by meteorological station networks. Even if they are, measurement devices are often destroyed or record inaccurate data since the wind speed often exceeds the range they are designed for. In a few cases, remote sensing by mobile radar systems, like the Doppler-On-Wheels (DOW), have been successful in measuring wind profiles of tornadoes but such systems have difficulties to capture the region close to the ground, and their successful deployment is rare compared with the occurrence of tornadoes and downbursts. Thus, estimates of the wind speed are usually derived *ex post* from the resulting damage. A grading of intensity is done either using the Fujita-scale (F-scale, Fujita, 1971) or the T-scale, (Meaden, 1976), or using both classifications. Although they were originally designed as wind speed scales, in practice they are applied as descriptive scales that distinguish various levels of damage to structures.

The relationship between wind speed and damage is rather complex and lacks comprehensive experimental support, especially at the higher intensities. The situation is aggravated by the large regional variety of building structures worldwide, which effectively hampers a globally uniform comparison of severe convective wind phenomena. In 2007, the "Enhanced Fujita-scale" was implemented in the USA (Potter, 2007). Its main innovation was the introduction of a large number of *damage indicators* (DI) to help improve wind speed estimates. However, several fundamental issues of the new scale are still under discussion (e.g., Doswell et al., 2009) and a simple adoption of the EF-scale would not yet be helpful or feasible in other regions worldwide. Vegetation damage has traditionally been considered in European damage assessments and was also briefly introduced to the EF-scale, but comprehensive information on this topic is still rather limited. Still, this approach has a large potential to infer wind speeds owing to the relatively constant stability of woody plants worldwide and the fact that information can be gathered from locations where no buildings or other structures are present.

While damage to adjacent buildings can further be used to relate tree damage to the wind speed scale at upper intensities, Beck and Dotzek (2010) have presented a concept to derive tornado intensity directly from the observed treefall pattern, provided the translation speed of the tornado is known and a sufficient number of trees had been downed to produce a consistent damage pattern. This underpins the importance of vegetation damage for intensity assessments in downbursts or tornadoes.

The aim of this paper is twofold: First, we wish to present the current status of tornado and downburst intensity rating in Central Europe based on a verbal damage description for the T- and F-scales considering both building structure and vegetation characteristics. It had originally been developed by European Severe Storms Laboratory (ESSL), Skywarn Germany and Munich RE members (Dotzek et al., 2000) but was so far only available in German. In a joint effort within the research project RegioExAKT (www.regioexakt.de), ESSL and Skywarn Germany we revised the verbal description and supplemented it by photographs of typical damage and new diagrams for damage vs. wind speed. Second, we discuss the description and the underlying methodology in the context of the desirable properties of a tornado intensity rating system (cf. Doswell et al. 2009), which should be broadly applicable, accurate and consistent. We also address remaining open questions and possible future developments.

The paper is organized as follows: Sec. 2 describes the methodology. In Secs. 3 and 4 the damage to wind speed mapping is presented and discussed. Sec. 5 gives conclusions and outlook.

2 Methodology

Any attempt to determine which typical property-, building-, and vegetation damage occurs with the different classes of the F-/T-scales should take into account desirable properties of a tornado intensity rating system, recently proposed by Doswell et al. (2009):

- *Broad applicability*: the rating system should resolve all physically possible wind speeds and provide enough damage indicators to be broadly applicable, whatever the local conditions along a given event's path.
- *Accuracy*: in order to provide a climatology of intensity for all reported events. Given the difficulty of estimating wind speeds from damage, this is a challenging requirement.
- *Consistency*: Ideally, the same process for ratings should be used everywhere through all time, to remove secular trends in the database.

Our target region is Central Europe. Previously, the term "Central Europe" was used by Dotzek et al. (2000) to refer to the three countries of Germany, Austria and Switzerland. However, our concept will be useful in more than these three Central European countries. In fact, it can be applied in any region with building standards or vegetation types comparable to those in the region considered here.

2.1 The F-and T-scales

Originally, both the F- and T-scales were defined as wind speed scales based on a nonlinear scaling with an empirical exponent of 3/2 inherited from the Beaufort (Bft) scale. Using the fixed points Bft 12 = v(F = 1) = 33 m s^{-1} (hurricane-force wind) and v(F = 12) = 330 m s^{-1} (Mach 1, speed of sound at -3°C), Fujita (1971, 1981) arrived at

$$v(F) = 6.302 \text{ m s}^{-1} (F + 2)^{3/2}. \quad (1)$$

The twice-as-fine T-scale (Meaden, 1976) formally extended the well-known Beaufort scale to higher (peak) wind speeds, while one T class comprises two Bft classes:

$$v(T) = 2.262 \text{ m s}^{-1} (T + 4)^{3/2}. \quad (2)$$

A thorough analysis of the scales' design was given by Dotzek (2009). Here, Table 1 gives an overview of the F- and T-scale classes and the related wind speeds. For this purpose, the slightly differing velocity thresholds of the two scales had been homogenized by Dotzek et al. (2000) such that two T classes correspond exactly to one F class. The scales reach from –2 to 6 (F-scale) and –4 to 13 (T-scale), respectively, but only the grades F0 to F5 or T0 to T11 are being applied in practice. Tornadoes (or downbursts) with negative scale values are so weak that they are unlikely to cause any damage. At the high end, theoretical studies support the occurrence of extreme near-surface wind speeds in the range of Fujita's F5 category or perhaps even beyond – see Fiedler and Rotunno (1986), Fiedler (1998), and Lewellen and Lewellen (2007). Yet, little evidence currently supports the existence of F6 tornadoes (Wurman et al., 2007).

The terms to coarsely classify tornado intensity in Table 1 follow Kelly et al., (1978): Weak (F0, F1), strong (F2, F3), and violent (F4, F5). Tornadoes with an intensity of F2 or greater are called significant, while tornadoes with negative F- or T-scale are named subcritical (Dotzek et al., 2003).

2.2 Building Structure and Loss Ratios

Fig. 1 shows the relation between damage (f) and wind speed (F) in form of an f-scale decision matrix like that originally proposed by Fujita (1992). Here, we include six different building types as DI typical for Central Europe when determining tornado or downburst intensity. This concept does not take into account a variety of DI as large as in the EF-scale currently used in the USA. However, this facilitates to relate the degrees of damage (DOD) noted verbally on the abscissa to loss ratios

$$L \text{ in } \% = \frac{\text{monetary damage}}{\text{reinstatement value}} . \quad (3)$$

The quantity “loss ratio” is often applied in the insurance industry. Values adapted for Central Europe were previously determined in cooperation with Munich RE (Dotzek et al. 2000). They distinguished loss ratios L_- and L_+ for two DI, respectively: “light” and “strong” buildings: “light” buildings were understood as storage depots, farm buildings (e.g., barns) and temporary structures, whereas “strong buildings” comprise permanent brick, stone or steel-reinforced structures, well-constructed frame houses with wind design as well as sturdy roof constructions (tiled, shingle or flat roofs).

Fig. 1 translates to a set of six loss ratio curves as shown in Fig. 2. For each curve, the strongest absolute increase in L occurs in a narrow range of wind speed. This reflects a maximum breakdown probability of structures around a specific critical destructive wind speed. It is however important to realize that at much lower wind speeds, especially when they occur over large areas, high amounts of accumulated damage may occur. These are signified by high claim ratios, even though loss ratios may still be below 1%, as described in Heneka and Ruck (2008). Experience shows that a loss ratio of 1% is a threshold of substantial building damage.

In an analysis of four winter storms, Heneka and Ruck (2008) identified 50.0 ± 8.0 m s^{-1} as the wind speed at which about half of all buildings are damaged in the affected area. From Fig. 2, loss ratios of 1% at 50.0 ± 5.0 m s^{-1} correspond to the range between the curves of weak and strong brick structures, respectively. This is indeed the predominant building type in Germany as imposed by regionally adapted building codes. The roof structure stability in Germany derived from Eurocode 1 and DIN standard 1055/4 (44 m s^{-1} for plains, 49 m s^{-1} for exposed hills and mountain ridges, 53 m s^{-1} for coastal areas) is shown in Fig. 3.

Note that the 50.0 m s^{-1} wind speed corresponds to the T4 and F2 thresholds above which damaging winds are called “significant” (Kelly et al, 1978).

At high wind speeds, the biggest uncertainty of this method lies in the actual wind speed to damage relation. Here, observations become increasingly rare and, thus, the available information from widespread wind damage at low speeds (e.g. in winter-season extratropical cyclones) and building codes had to be extrapolated. Another uncertainty concerns the relation between DOD and loss ratio, since even if a building was not completely destroyed, monetary loss may already approach 100% (De Silva et al, 2008). A third source of uncertainty is the assignment of the proper DI considering the construction quality and state of preservation of an individual building.

2.3 Vegetation Characteristics and Ensemble-based Loss Ratios

As the stability of woody plants is certainly much more uniform worldwide as that of buildings, a scientific overview of vegetation damage analysis is important and desirable. The use of damage assessments in forests and agricultural areas of the USA was discussed by Fujita (1989), in contributions to a Symposium on the F-Scale (Peterson 2003, Guyer and Moritz, 2003) and by Holland et al. (2006). In Europe since the 19th century, there has been a tradition to put emphasis on the assessment of forest damage occurring with winter cyclones or severe local storms like tornadoes and downbursts. Treefall patterns in forests have been considered in detail already by Martins (1850), Reye (1872), Wegener (1917), Letzmann (1923, 1925) and more recently by Dotzek et al. (2008), Bech et al. (2009) as well as Beck and Dotzek (2010). Hubrig (2004) published a comprehensive analysis of tornado and downburst wind damage to trees. This study was based on his own field studies, added by case studies and investigations about tree-statics of other European authors (Sinn, 1991; Sinn and Sinn, 1992; Mattheck, 1992; Wessolly and Erb, 1998; Gaffrey, 2002; Gaffrey and Kniemeyer, 2002).

In contrast to building structures, it is not straightforward to define a loss ratio for a single woody plant, since it may be damaged as a whole by breaking or uprooting or partially by loosing branches. Therefore, we define an ensemble-based vegetation loss ratio as the percentage of damaged objects, that is, a (homogeneous) stand with half of the trees uprooted would correspond to a loss ratio of 50%. Fig. 4 illustrates the vegetation loss ratio curves which are translated again into an f-scale matrix given in Fig. 5. Since no woody plant will survive wind speeds beyond about 75 m s^{-1} (i.e., the F3-F4 transition regime) without severe damage, it becomes more difficult to find specific vegetation damage for violent tornadoes.

Qualitative DI for the highest intensities are debarking of isolated remaining tree ruins, breaking of very strong tree trunks, up to exceptional damage like well-rooted large trees or even stubs being ripped out of the ground.

3 Damage to Wind Speed Mapping

3.1 Illustration of Typical Wind Impact to Building Structures

The damage description of Table 2 is supplemented by photographs of typical damage (panels (a) of Figs. 6–16). We caution that these illustrations (as those for the vegetation damage) are exemplary and not meant to be used as the sole guidance for damage surveys. Any rating given for these cases was not based exclusively on the damage shown in these photographs. Rather, all available damage information on the specific sites was taken into account in order to get as much ensemble data as possible.

Fig. 6a shows some marginal (T0) wind effect in form of isolated slightly shifted non-bracketed tiles in an exposed position, likely caused by a trailing vortex from the ridge of the roof. This marginal damage is on the border to T1 and it is difficult to find T0 damage since it is likely overlooked. The garden fence panels in Fig. 7a (T1) are an example for a damaged weak and vulnerable structure. Light roof damage (slightly displaced tiles) was found in the vicinity of that site. The gradually increasing DOD to tiled roofs is documented in Figs. 8a (T2) and 9a (T3). The storm causing the damage depicted in Fig. 10a was rated T4 due to the structural damage to the walls of the barn as well as the complete loss of the roof construction and the closed gates. Besides that, also F2 tree damage was found close to the barn. In Fig. 11a (T5), the supporting structure of an aged roof was completely gone on one side with visible damage to the upper edge of the brick wall. F3 damage is shown in Figs. 12a (T6) and 13a (T7). Whereas in Fig. 12a the walls of the unroofed outbuilding partially collapsed, in Fig. 13a the upper story is completely destroyed. Note that the intact birch tree in Fig. 12a was outside the tornado path. Figs. 14a displays a prefabricate house (strong frame house) with brick facing which was blown down (T8). In Fig. 15a, one finds most of a strong brick structure collapsed but not yet blown down completely, leading to a T9 rating. For the F5 cases we refer to examples from the USA since we presently lack adequate photographic material from F5 tornadoes in Central Europe. The only gradual difference between Fig. 16a and Fig. 17a is that in the latter a strong frame house is completely blown away from its foundations and, thus, distinguishing T classes at the high end of the scale is hardly possible. It should be noted that in this case (Bridge Creek tornado on 3 May 1999), a DOW radar detected winds of 134.0 ± 9.0 m s^{-1} at a height of 32 m above ground level (AGL) (Wurman et al., 2007).

3.2 Illustration of Typical Wind Impact to Vegetation

The second column of Table 2 is based on Hubrig (2004). Again, the damage photographs (panels (b) in Figs. 6-16) are exemplary, and more information than shown here (including damage to building structures in some cases) was taken into account for the intensity rating. First marginal vegetation damage (T0) in form of snapped small twigs and dead or diseased branches is shown in Fig. 6b. Already at T1 intensity, weakly enrooted trees on unstable ground can be uprooted, as the example of a spruce tree on stagnant moisture soil demonstrates (Fig. 7b). A quite frequent damage type during the growing season is irreversible bending of tree stems (Figs. 8b and 9b). At higher intensities, the occurrence of this effect is strongly reduced in favour of snapping.

Since trees adapt naturally to the wind climate in a given region, widespread snapping or uprooting of strong tree stands is expected for extreme, rare wind gusts. For Central Europe, the 50-year wind speed – which by definition is exceeded with a probability of 2% in one year – lies around 40 m s^{-1}. Fig. 10b (T4) shows a damage swath in a healthy beech forest where better-adapted edge trees survived. At T5 intensity (Fig. 11b), this is not the case any more for even edge trees, wind-proof hedges, and strong solitary trees are heavily damaged. Above T5 intensity, no native woody plants survive – if the stem remains – without severe damage (Figs. 12b – 17b). A qualitative indicator for violent winds is the debarking of remaining tree ruins. Exceptional damage, like the uprooting and throwing of large tree stubs, can also serve as evidence of violent tornadoes. A historic example is the F5 Woldegk, Germany, tornado of 1764 during which oak stubs that only protruded by about 0.3 m, were pulled out of the ground.

4 Discussion

Doswell et al. (2009) proposed desirable properties of a tornado intensity rating system, which should be broadly applicable, accurate and consistent. Within the ongoing debate about the currently applied EF-scale, its implications for tornado ratings outside the USA have to be addressed. Over the last ten years, awareness of convective severe wind phenomena in Europe has increased significantly and the F- or T-scales have become widely accepted.

Our presented damage description does not rely on a single DI, but rather takes into account all available information for each case, including damage to vegetation. It aims to provide a guideline helping to achieve consistent damage assessments, and it benefits from the fact that construction standards in Europe are more homogenous and generally higher than in the central parts of the USA. The description of vegetation damage updates and extends Hubrig (2004). It has been applied by Svabik and Holzer (2005) in their analysis of tornadoes and, for instance, by Pistotnik et al. (2010) for an F3 downburst in Austria.

Note that the European Severe Weather Database (ESWD, www.eswd.eu) provides a unique source not only for climatology but also for wind engineering purposes. A three-level quality control system is applied to the ESWD and the source of rating-relevant information is part of the metadata accompanying a report (Dotzek et al. 2009). The tornado and downburst intensity distributions of all rated events in the ESWD have been compared to those from the USA by Dotzek et al. (2009). The distributions were found to be very similar except for a greater underreporting of weak tornadoes (F0) in Europe. This demonstrates that the rating based on the methods presented here is consistent with the F-scale rating in the USA and gives confidence that worldwide homogeneity of tornado and downburst intensity ratings is possible. Thus, two of the aforementioned properties – broad applicability and consistency – could be fulfilled by our damage description adapted to Central Europe.

However, considering the third property – accuracy – the link between the wind speed intervals and the regional damage description is still preliminary and relies on extrapolations to higher intensities. Heneka and Ruck (2008) show a quite large scatter in the frequency of damage (claim ratio) and also in the DOD (loss ratio) for a given wind speed due to different quality of building structures. This could be partly overcome in our proposed method by taking into account different building characteristics and ensembles, but the general damage to wind speed relation definitely calls for further investigation.

Concerning vegetation damage, the main shortcoming lies currently in the low number of investigated cases beyond T5 intensity. Generally, it can be concluded that larger homogenous forests are only suitable as a DI up to T4 or T5, that is, F2 intensity, since they will be completely destroyed by higher wind speeds. Robust solitary trees and forest edges can provide differentiated information for rating purposes up to T6/F3. Indicators for violent winds are the debarking of remaining tree ruins as well as exceptional damage like well-rooted tree stubs being ripped out and drifted over large distances. However, these criteria are rather qualitative since, for example, the degree of debarking depends not only on the wind speed but as well on the amount of flying debris, and the strength or thickness of the bark.

The concept to derive tornado intensity directly from treefall patterns (Beck and Dotzek, 2010) may be a solution to this problem, if detailed damage surveys or aerial photography are available, as already recommended by Letzmann (1939) (cf. Peterson, 1992).

With respect to rating in practice, one should consider the destructive nature of the wind effects under discussion. The DOD is, thus, determined by the maximum wind speed occurring during the event at a given location. On the other hand, the accuracy of a "maximum rating" based on singular damage is limited and we suggest taking into account ensemble information whenever it is possible. It is possible that future studies continue to show a large scatter in claim and damage ratios for a given quality of building structure and a given wind speed (Heneka und Ruck, 2008). In that case, one step to take these uncertainties into consideration could be to widen the wind speed ranges of a given F- or T-class effectively creating an overlap between neighbouring classes. At this time, we were not able to find a method that allows us to determine the appropriate amount of overlapping for this requires additional research, for instance, from wind engineering.

5 Conclusions and Outlook

We have presented a tornado and downburst intensity rating system based on wind speed scales (T- and F-scales) with regionally-adapted damage descriptions for building structures and vegetation in Central Europe. The similarity of the intensity distributions in the USA and Europe (Dotzek et al. 2009) is a strong indication for its broad applicability and shows that worldwide homogeneity of tornado rating is feasible. In spite of the consistency among the distributions, the absolute relation of wind speed vs. damage is not yet known accurately, in particular in the upper range of intensities. Consequently, estimating wind speeds from damage remains challenging.

Our work also contributes to ongoing discussions about the EF-scale that is applied in the USA. Dotzek (2009) recently proposed the Energy- or "E-scale" based on a nonlinear scaling of physical quantities which results in a universal wind speed-scale relation which is always linear in v. This offers to treat nonlinear scaling of damage-related physical properties (wind pressure ~ v^2, energy current density ~ v^3) separately. Finally, we suggest some directions of ongoing and further research on wind speed vs. damage: In the upper range of intensities, exceptional damage occurs due to impact of wind-driven debris, which could be investigated in a laboratory experiment. The reported cases of airborne heavy objects like vehicles call for studies on aerodynamic wind effects. A promising field for case studies with widespread events is damage caused by convective cells embedded in winter-season extratropical cyclones. These are known to be associated with peak wind gusts up to F3 intensity (upper-air momentum transfer to downbursts at the ground) and tornadoes. More direct measurements of near-ground (tornadic) wind fields are expected to from ongoing field campaigns, like VORTEX2. Suggestions for further discussion are welcome and contriubutors are invited to contact the authors via windscales@essl.org.

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Tables

Table 1: Overview of the F- and T-scale, the related (homogenized) wind speeds (Dotzek et al., 2003).

Category		F-scale	T-scale	v in m s^{-1}
	subcritical	F–2	T–4	1.0 ± 1.0
			T–3	3.5 ± 2.5
		F–1	T–2	9.0 ± 3.0
			T–1	15.0 ± 3.0
	weak	F0	T0	21.5 ± 3.5
			T1	29.0 ± 4.0
		F1	T2	37.0 ± 4.0
			T3	41.0 ± 4.5
significant	strong	F2	T4	55.0 ± 5.0
			T5	65.0 ± 5.0
		F3	T6	75.5 ± 5.5
			T7	87.0 ± 6.0
	violent	F4	T8	99.0 ± 6.0
			T9	111.0 ± 6.0
		F5	T10	123.5 ± 6.5
			T11	136.5 ± 6.5

Table 2: Verbal description of typical wind impact to property and vegetation (cf. Dotzek et. al, 2000, Hubrig, 2004) for the T-/F-scale ranging from T0 (21.5 ± 3.5 m s^{-1}) to T11 (136.5 ± 6.5 m s^{-1}).

T(F)-Scale	Property Damage	Vegetation Damage
T0 (F0–)	Loose light objects lifted from the ground. Scaffolding can be overthrown; light damage to marquees and tents can occur. Tiles at exposed positions can become loose. No damage supporting structures.	Few weak branches start to break; path is visible in meadows or crop fields. Diseased (e. g. rotting) or particularly unstable trees (slender stem; elevated crown; poor shallow rootage) can break or be uprooted (root rotting or unstable wet soil).
T1 (F0+)	Light objects and garden furniture can be overthrown or become airborne; wooden fences can be overthrown. Light roof damage (tiles and metal sheeting can become loose and may be blown down). Marginal damage to light outbuildings; no structural damage.	Strong and healthy branches start to break, particularly during growing season (leafy deciduous trees). Diseased (e. g. rotting) or particularly unstable trees (slender stem; elevated crown; poor shallow rootage) break or are uprooted frequently (in particular in cases of root rotting or unstable wet soil).
T2 (F1–)	Heavier objects are lifted from the ground and can become dangerous projectiles. Caravans and trailers can be overthrown. Noticeable damage to tiled roofs and unstable flat roofs. Marginal to medium damage to light outbuildings; first damage to structural elements of solid buildings possible.	Numerous strong and healthy branches break more frequently, particularly during growing season (leafy deciduous trees). Most trees with rotting or other structurally relevant damage, unstable trees (slender stem; elevated crown; poor shallow rootage) or trees on unstable or wet soil are broken or uprooted throughout. Even healthy trees can be broken or uprooted in cases of unfavourable gust direction or timing or sodden soil. During growing season trees with stable rooting but unstable stem become permanently bent.
T3 (F1+)	Numerous caravans and trailers are overthrown. Tiled roofs and unstable flat roofs suffer major damage. Medium damage to light outbuildings; isolated damage to structural elements of solid buildings. Driving cars are pushed off road.	Numerous strong and healthy branches break. Even stable and healthy trees are increasingly uprooted or already broken. Quite frequent permanent bending during growing season. Substantial damage to stable wood, where the most stable trees and underwood, which features small aerodynamic drag, predominantly survive.
T4 (F2–)	Heavy damage to vehicles and trailers. High threat and damage due to flying debris. Roofs are completely untiled. Severe Damage to light outbuildings; increasing damage to structural elements of solid buildings; gables can collapse.	Even stable trees and woods are almost completely uprooted or broken. Large trees break most likely if well-enrooted. Numerous strong and healthy branches break even out of growing season (bare deciduous trees). The fraction of permanent bending is strongly reduced compared to snapped trees.
T5 (F2+)	Severe damage to roofs, annexes and light outbuildings. Increasing damage to structural elements of solid buildings. Collapse of single weak buildings (agricultural structures and storage depots). Vehicles can be lifted from the ground.	Even most stable woody plants as edge trees, wind-proof hedges and bushes are strongly damaged or destroyed either by uprooting, stem or crown break or due to tearing off most of the branches (even bare trees out of growing season), in particular almost complete loss of brushwood.
T6 (F3–)	Light outbuildings are widely destroyed. Severe damage to structural elements of solid buildings. Single buildings collapse. Heavy vehicles are lifted or overthrown.	No native woody plants survive – if the stem remains – such a strong wind without severe damage. Remaining trees are extensively debranched.

T7 (F3+)	Widespread complete destruction of light outbuildings and severe damage to solid buildings. Numerous buildings collapse.	No native woody plants survive – if the stem remains – such a strong wind without severe damage. Remaining trees are extensively debranched and isolated debarking due to small high speed particle (like sand or debris) impact starts to take place.
T8 (F4–)	Severe damage to solid buildings. Widespread collapse of buildings; furniture is blown away. Vehicles are thrown over large distances.	Significant debarking of tree ruins due to small high speed particle (like sand or debris) impact.
T9 (F4+)	Predominant total loss of solid buildings. Trains are dragged from their track.	Significant or already total debarking of tree ruins due to small high speed particle (like sand or debris) impact.
T10 (F5–)	Predominant total loss of solid buildings.	Total debarking of tree ruins due to small high speed particle (like sand or debris) impact. Exceptional damage: tree stubs are ripped out and drift over large distances.
T11 (F5+)	Almost exclusively total loss of solid buildings. Clear distinction to T10 is difficult.	Total debarking of tree ruins due to small high speed particle (like sand or debris) impact. Exceptional damage: tree stubs are ripped out and drifted over large distances.

Figure captions

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Fig. 2: Loss ratio curves for buildings as function of the wind speed adapted for Central Europe.

Fig. 3: Wind zones for Germany derived from building code DIN 1055/4.

Fig. 4: Loss ratio curves for vegetation as function of the wind speed adapted for Central Europe. Progressive debarking sets in at upper F3 intensities and becomes an indicator for violent winds (F4, F5). However, the degree of debarking depends not only on the wind speed but as well on the amount of flying debris, and the strength or thickness of the bark.

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Fig. 6: T0 (F0–) damage. (a): Tiles slightly displaced. Downburst, 18 January 2007, Pulheim (Germany), Photo: Erik Dirksen. (b): Leaves, small twigs and dead branches snapped. Downburst, 4 June 2003, Schillig (Germany), Photo: Martin Hubrig.

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Fig. 10: T4 (F2–) damage. (a): Barn ruined, Photo: Erik Dirksen. (b): Swath in beech forest with remaining edge trees, Photo: Bernhard Pohl. Both panels from tornado, 13 May 2007, Kall-Sistig (Germany).

Fig. 11: T5 (F2+) damage. (a): Aged roof structure partly destroyed. Tornado, 18 July 2004, Tönisvorst (Germany), Photo: Thomas Sävert. (b): Heavily damaged edge trees. Tornado, 29 June 1997, Bissendorf (Germany), Photo: Martin Hubrig.

Fig. 12: T6 (F3–) damage. (a): Largely demolished and partly collapsed outbuilding. Tornado, 10 June 2003, Acht (Germany), Photo: Matthias Habel. (b): Completely destroyed sturdy but exposed forest edge. Downburst, 1 March 2008, Braunau am Inn (Austria), Photo: Alois M. Holzer.

Fig. 13: T7 (F3+) damage. (a): Upper storey of outbuilding completely destroyed. Tornado, 23 June 2004, Micheln (Germany), Photo: Martin Hubrig. (b): Destroyed solitaire trees with isolated debarking. Tornado, 22 July 2007, Turiysk (Ukraine), Photo: Olexandr Khilchuk.

Fig. 14: T8 (F4–) damage. (a): Prefabricate house with brick facing blown down. Tornado, 3 August 2008, Hautmont (France), Photo: Bjoern Stumpf. (b): Ruined beech trees with distinct partial debarking. Tornado, 1 June 1927, Auen (Germany), Photo: Heinz Brinkmann.

Fig. 15: T9 (F4+) damage. (a): Massive (brick) house ruined down to base walls. Tornado, 3 August 2008, Hautmont (France), Photo: Bjoern Stumpf. (b): Largely debarked Tree. Tornado, 10 August 1925, Borculo (Netherlands), Photo: Stormrampmuseum Borculo.

Fig. 16: T10/11 (F5) damage. (a): Complete destruction (total loss) of buildings. Tornado, 3 May 1999, Moore, OK (USA), Photo: Mike Branick, NWSFO. (b): Widely debarked tree and destroyed pickup truck. Tornado, 3 May 1999, Moore, OK (USA), Photo: Kevin Kelleher.

Fig. 17: T10/11 (F5) damage. (a): Buildings blown away from foundation. Both panels tornado, 3 May 1999, Moore, OK (USA), Photos: Mike Branick, NWSFO. (b): Completely debarked solitaire tree ruins.

Fujita damage class	f0	f1	f2	f3	f4	f5
loss ratio (%)	0.1	1	10	50	90	100
degree of damage → ↓ damage indicator	light roof damage	significant roof damage	roof gone	walls partly collapsed	largely blown down	blown away
weakest outbuilding	**F0+**	**F0+**	**F1-**	**F1-**	**F1+**	**F2-**
outbuilding	**F0+**	**F1-**	**F1+**	**F2-**	**F2+**	**F3-**
strong outbuilding/ weak framehouse	**F0+**	**F1+**	**F2-** *10*	**F3-** *12*	**F3+**	**F4-**
weak brick structure/ strong framehouse	**F1-** *8*	**F1+** *9*	**F2+** *11*	**F3+** *13*	**F4-** *14*	**F5** *16 17*
strong brick structure	**F1-**	**F2-**	**F3-**	**F4-** *15*	**F5**	**F5**
concrete building	**F1-**	**F2+**	**F3+**	**F4+**	**F5**	**F5**

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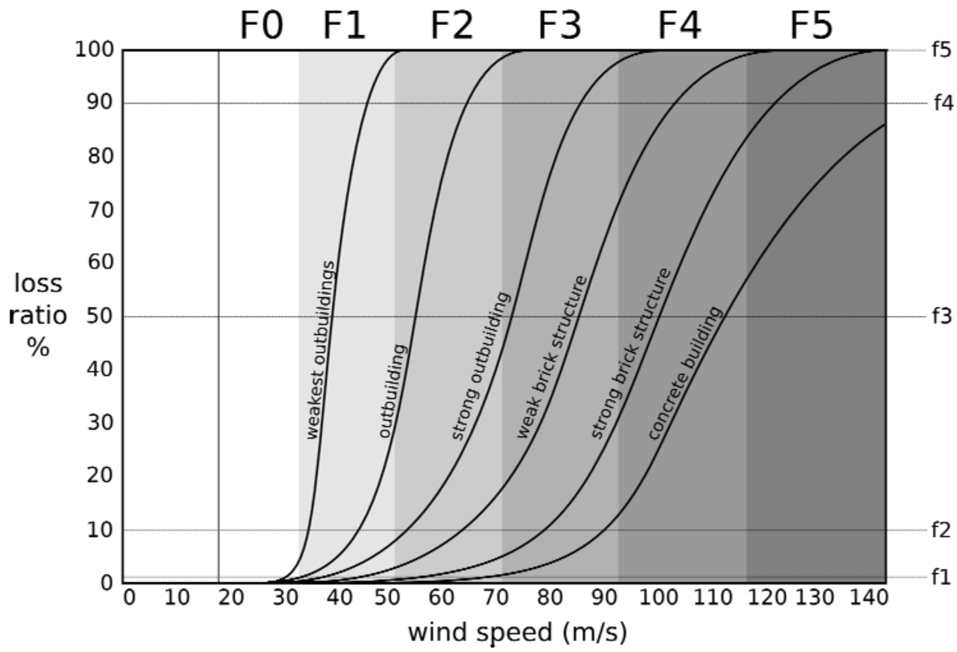

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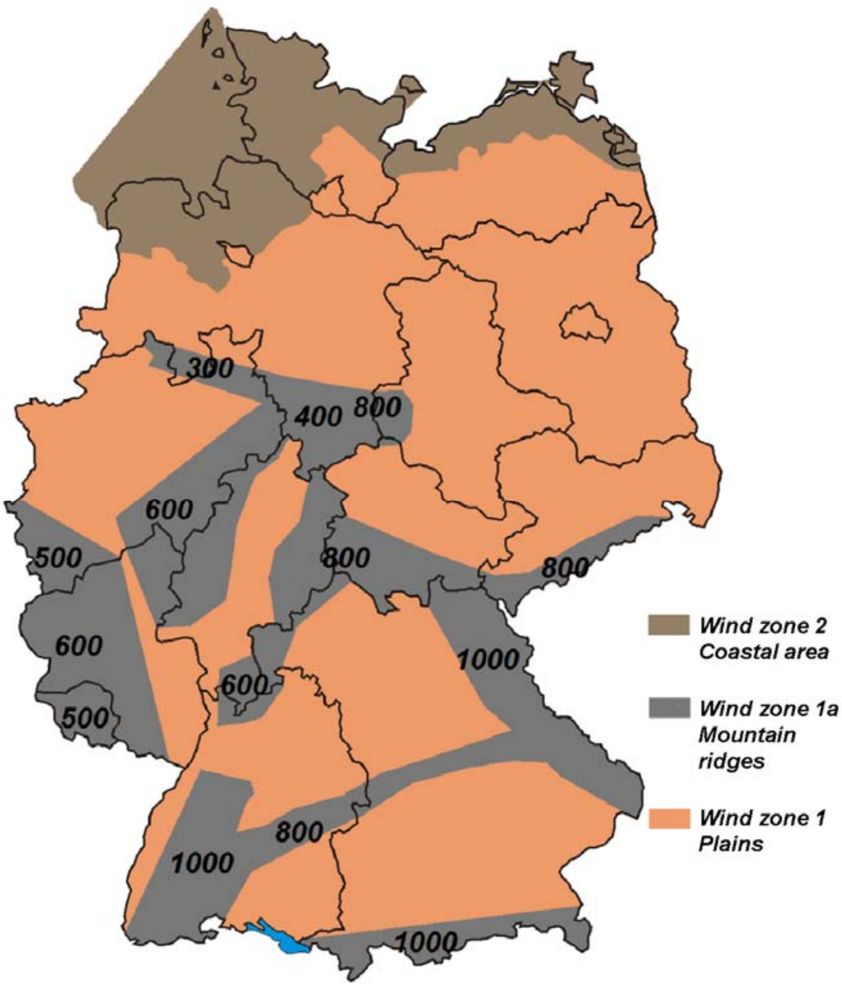

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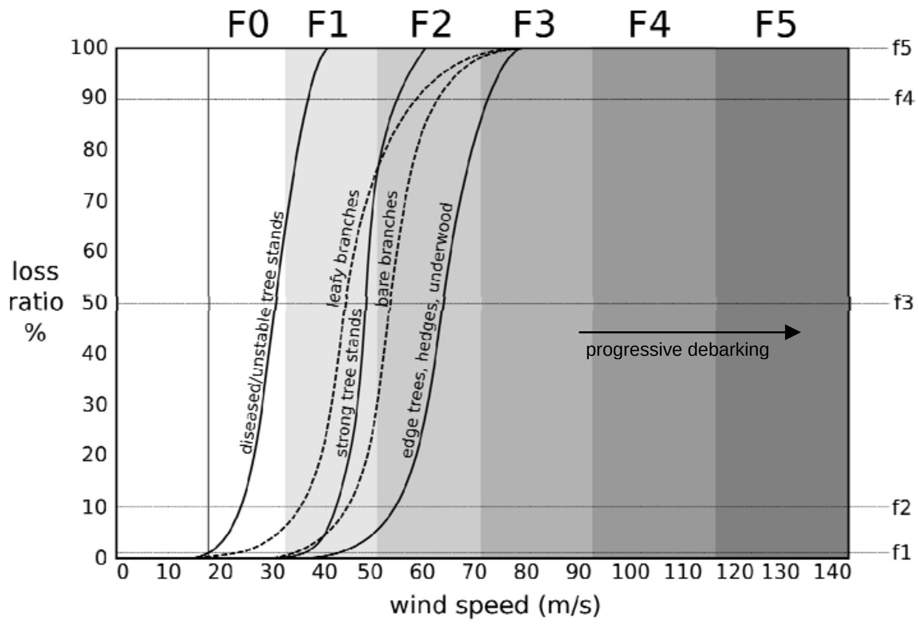

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Fujita damage class	f0	f1	f2	f3	f4	f5
loss ratio (%)	0.1	1	10	50	90	100
damage prevalence → ↓ damage indicator	extremely isolated	isolated	significant	frequent	prevalent	total
branches - leafy	**< F0**	**F0+**	**F1-**	**F1+**	**F2-**	**F3-**
- bare	**F0-**	**F1-**	**F1+**	**F2-**	**F2-**	**F3-**
tree stands - diseased/ unstable	**< F0**	**F0-**	**F0+** *7*	**F0+** *8*	**F1-**	**F1-**
- strong	**F0+**	**F1-**	**F1+**	**F1+** *9*	**F2-** *10*	**F2-**
edge trees, hedges, underwood	**F1-**	**F1+**	**F2-**	**F2+** *11*	**F3-** *12*	**F3-**

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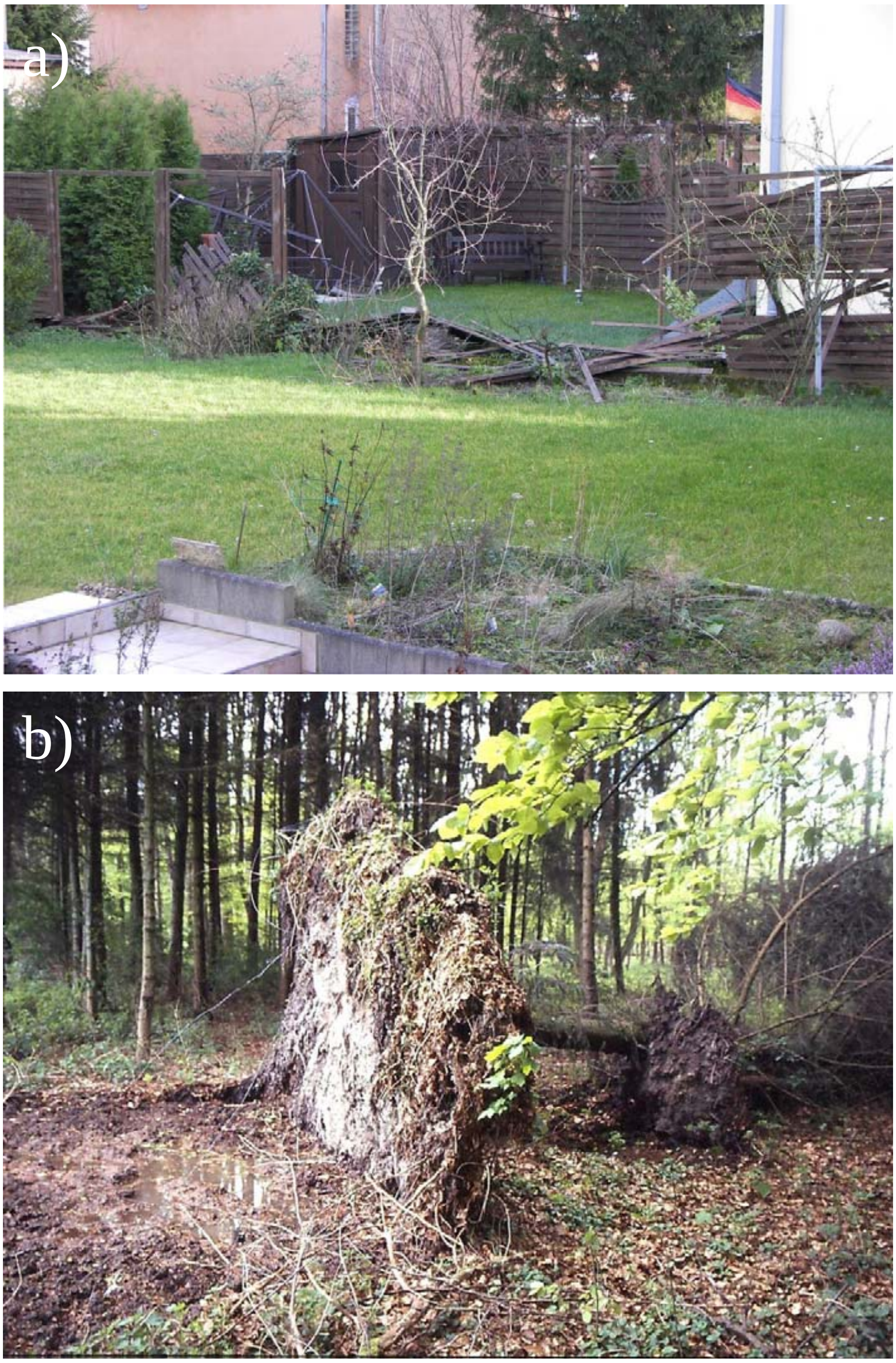

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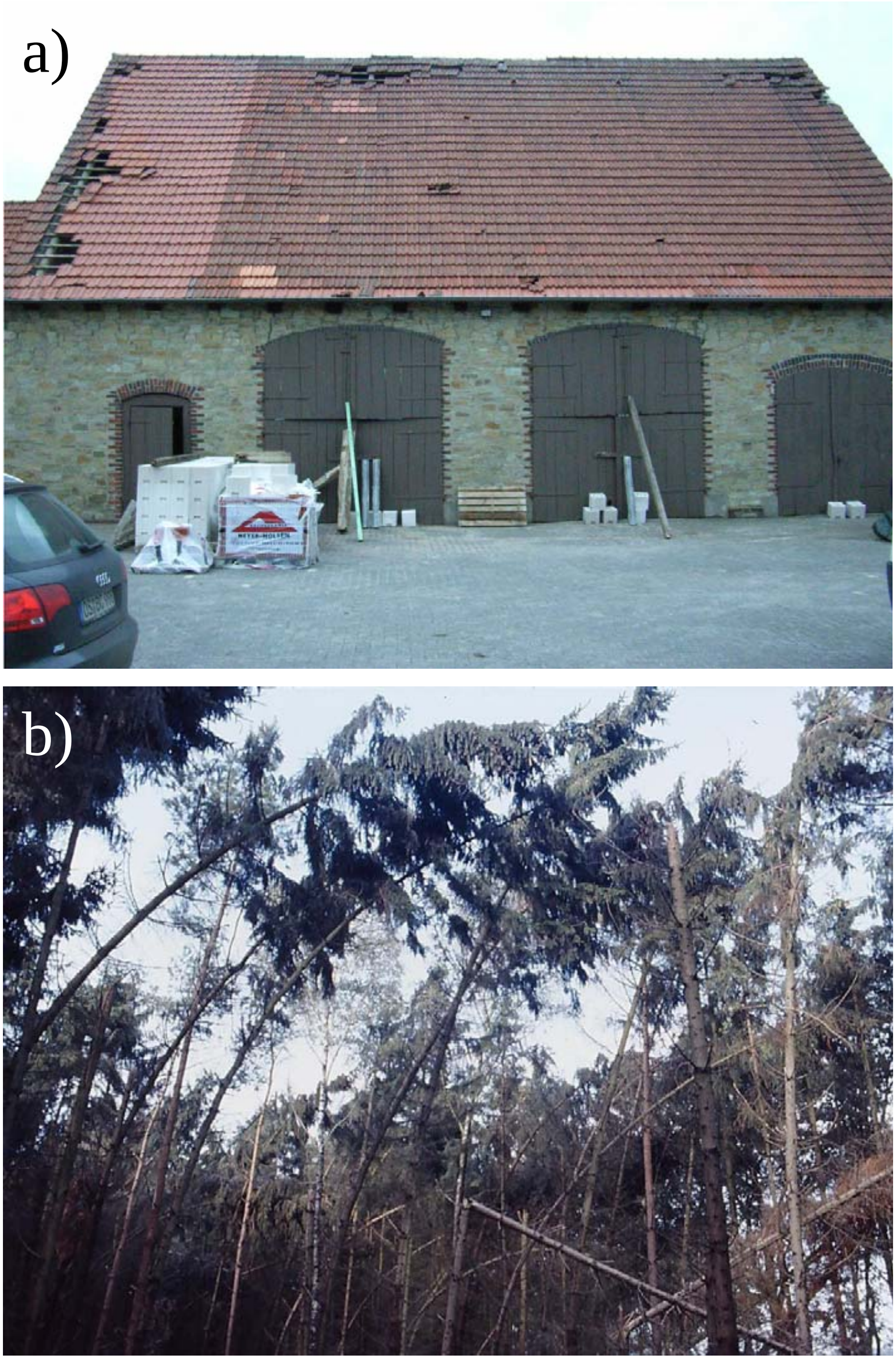

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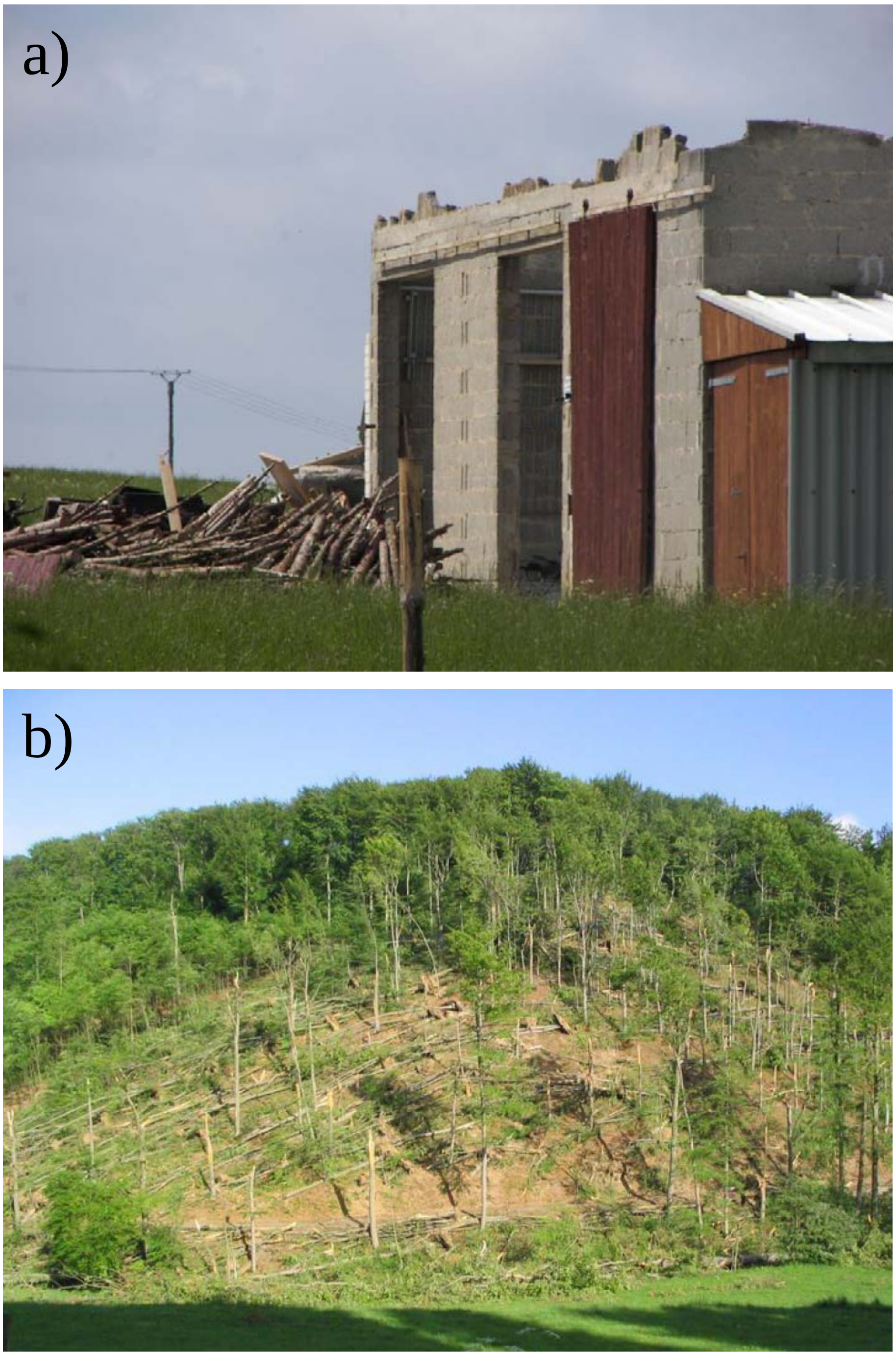

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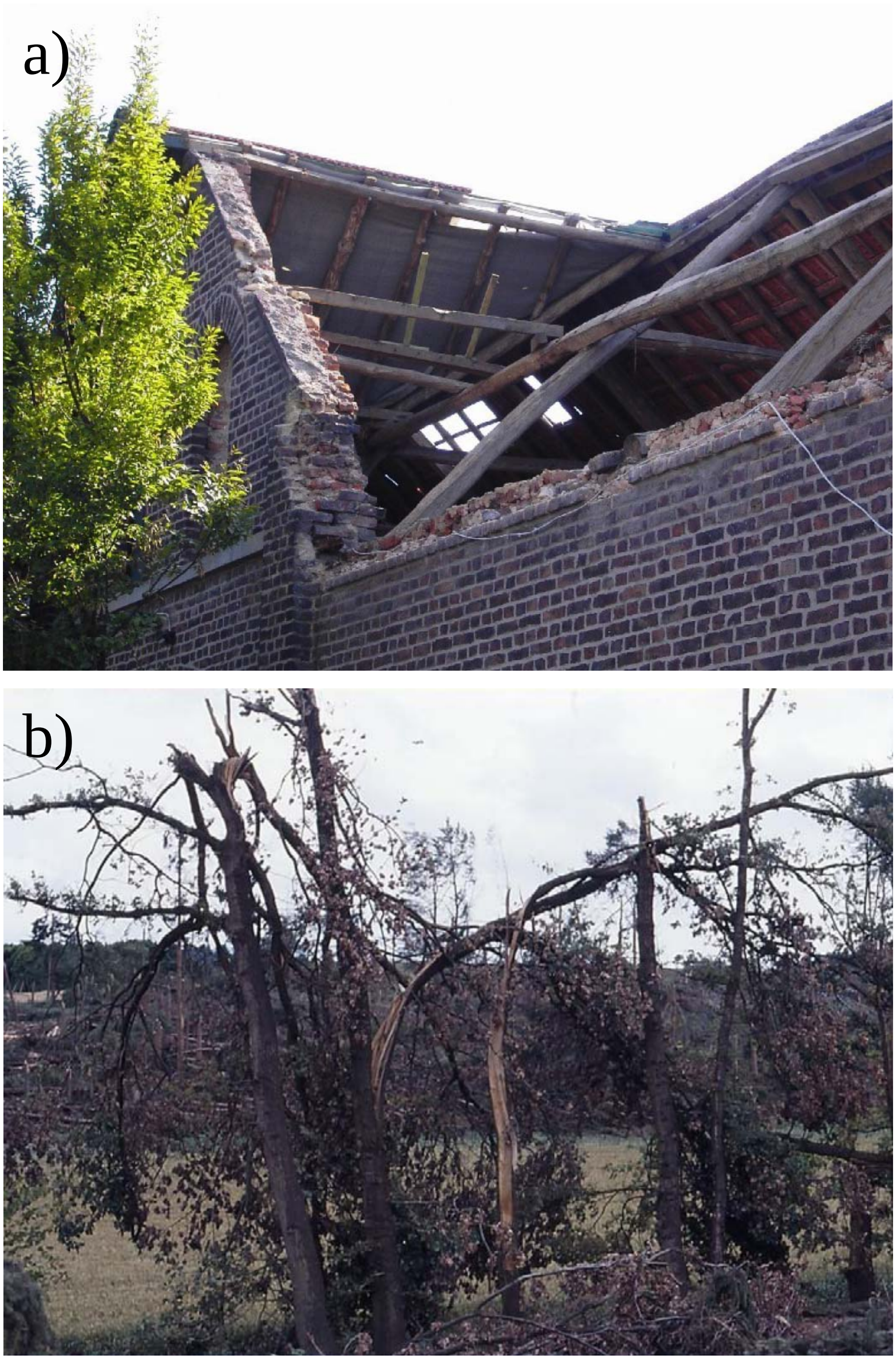

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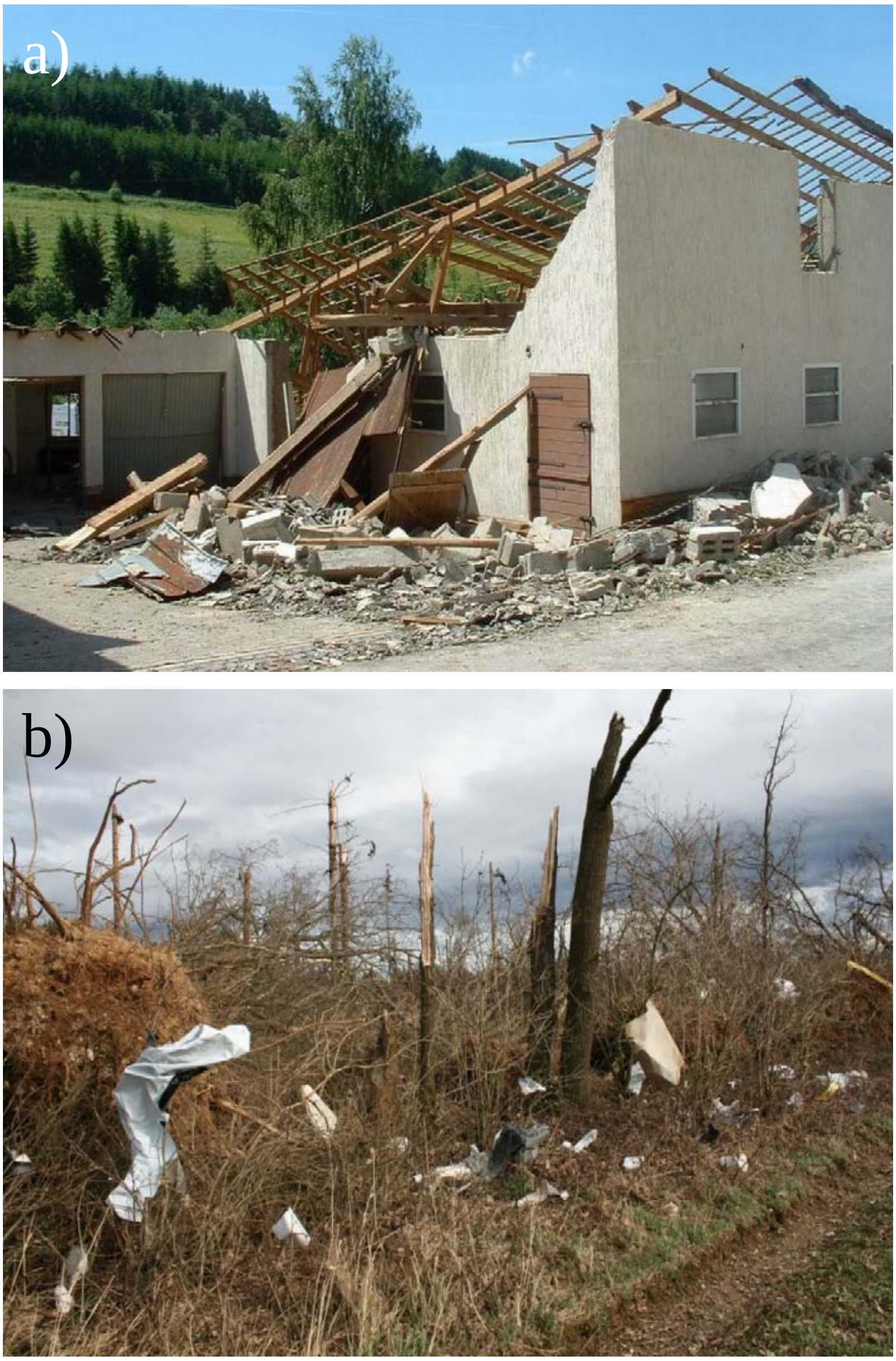

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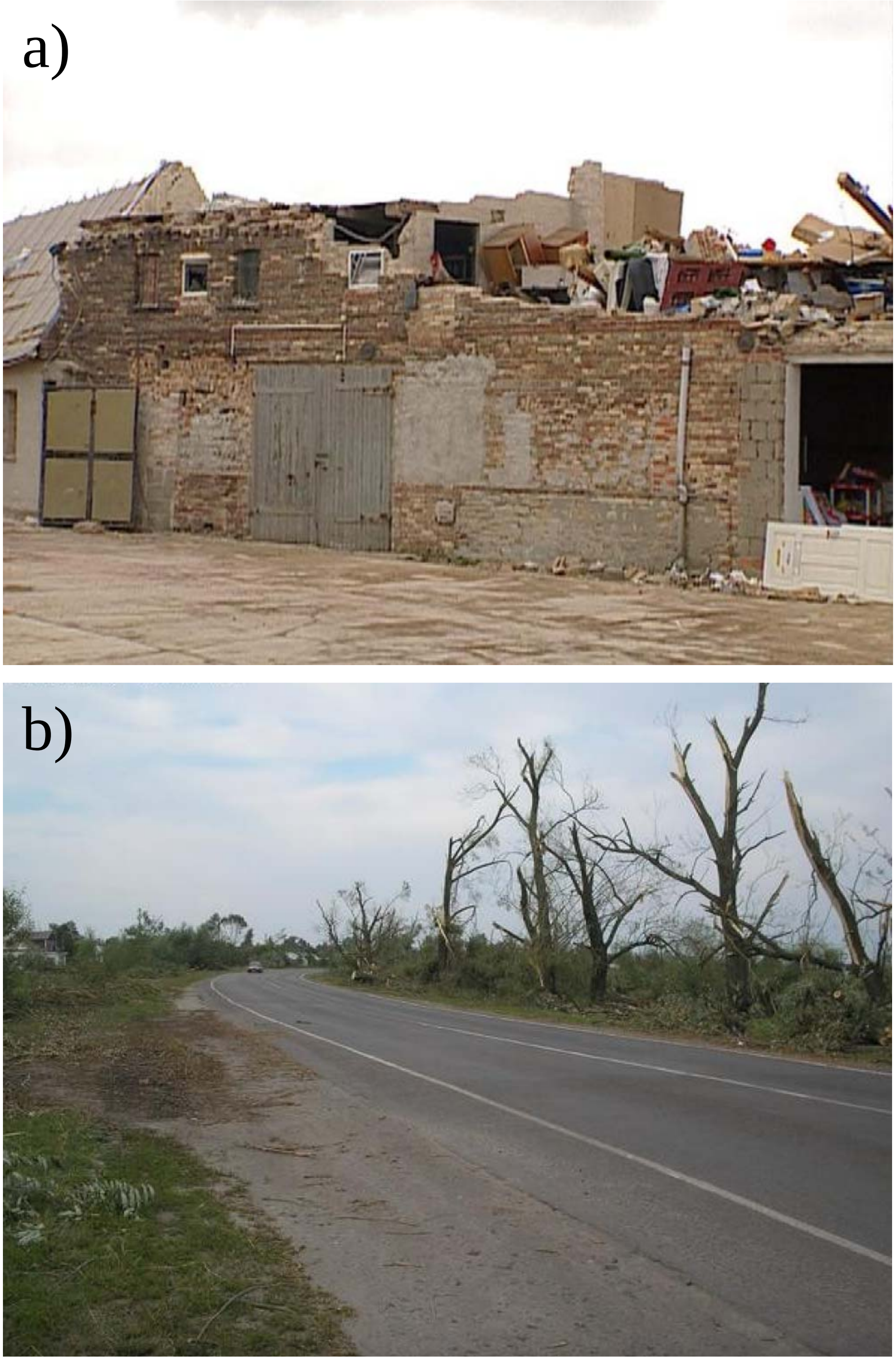

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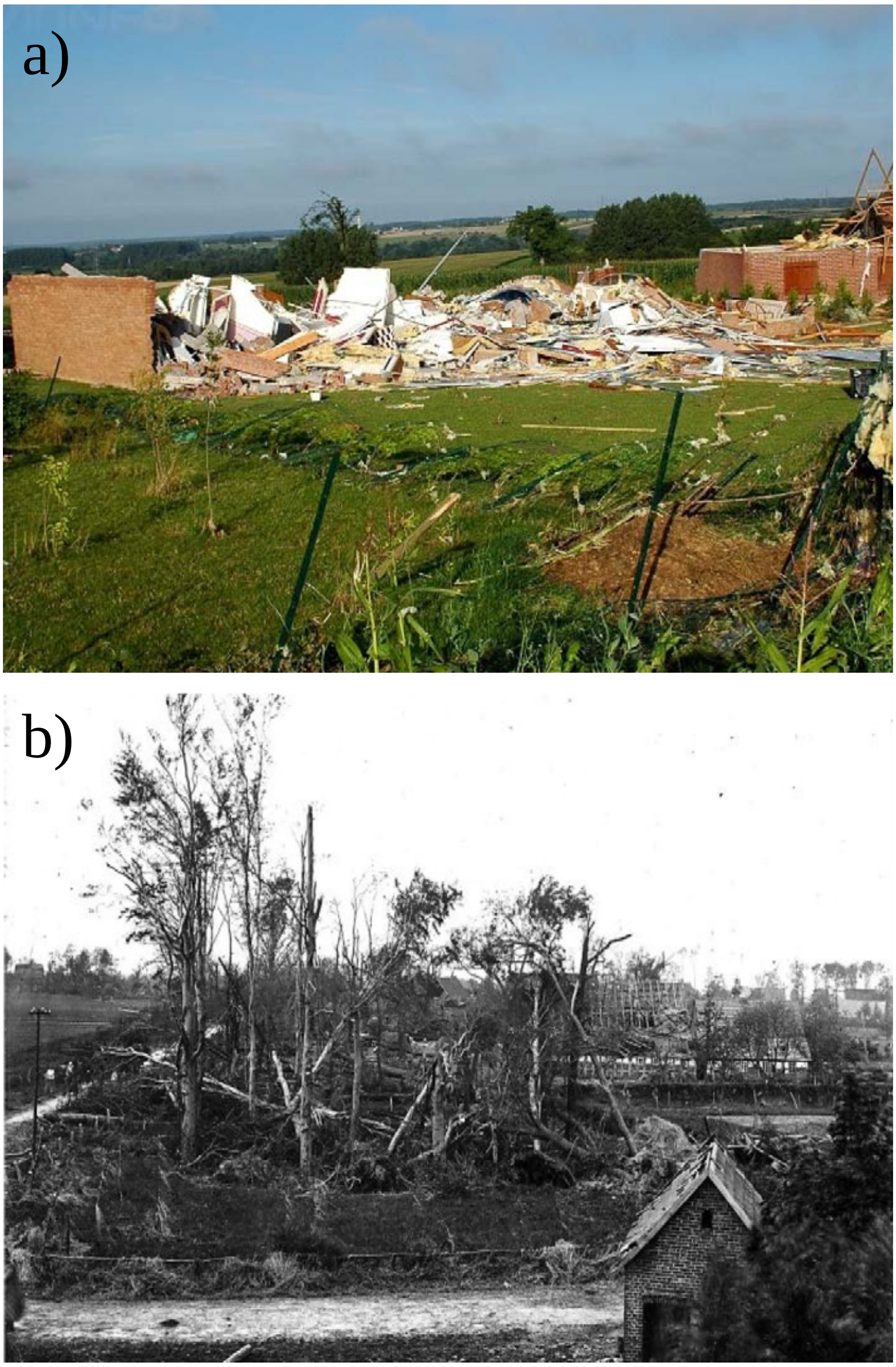

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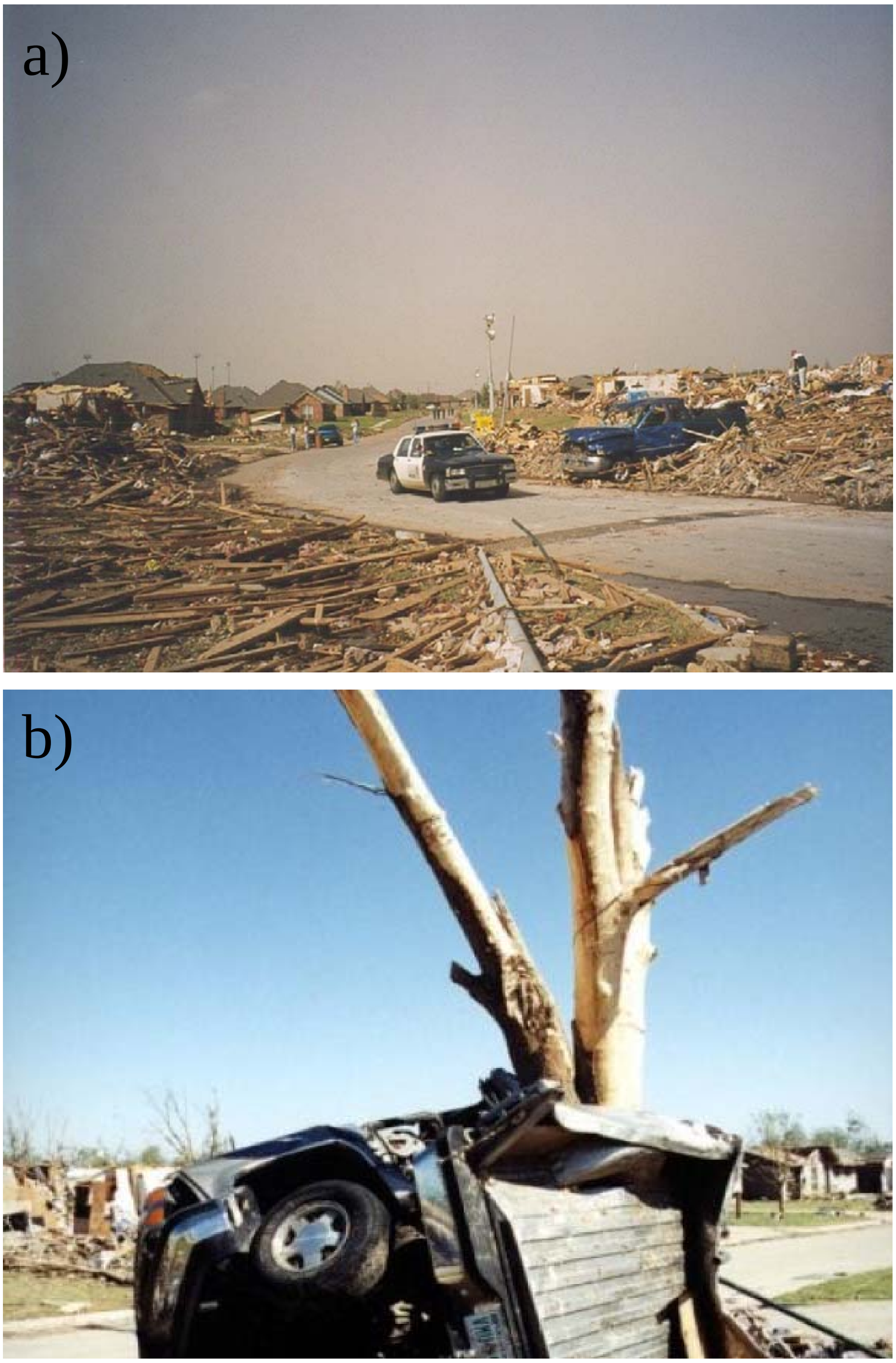

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