Chapter 14

Unknown tipping-points: a method for anticipating future forest disturbance risk

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One ecologically interesting by-product of the First Industrial Revolution (c. 1760−1830) was the case of the peppered moth (*Biston betularia*) (Kettlewell, 1955). Soot from coal burning darkened the forests surrounding major industrial centers in England by the early to mid-19th century (Hof et al. 2016). The environmental darkening was so significant that it resulted in a change in the dominant color variety of the moth. Before the first industrial revolution, the lighter variety (i.e., *B. betularia typica*) was the most common form of peppered moth. The resting moth's whitish coloration blended in with the lighter color bark of the birch (*Betula* spp.), which were common in the areas around industrial centers. The darker colored variety of peppered moth (i.e., *B. betularia carbonaria*) was also present, but in lower numbers. Their greyish/black color stood out against the white bark of the birch trees, and they were thus easy prey for their primary predators (e.g., birds). However, by the 1830s, industrial soot had blacked the birch sufficiently to shift the camouflage advantage to the darker variety of the peppered moth. Therefore the lighter variants of the peppered moth declined, and the darker moths became more numerous. By the 1960s, coal became a less dominant source of fuel, and the dominance of the lightercolored moths returned to the moth's preindustrial population level of the mid-1800s as the birch bark again became lighter (Hof et al., 2016). A few entomologists observed the distribution of color variants in the peppered moth (Cooke,1877). Still, there is no record of a researcher foreseeing the change in moth color dominance because of the accumulating soot. The historical curiosity of the peppered moth had no significant ecological impact, but this may be the earliest documented unexpected, nonantecedent event caused by the industrial age.

By definition, a previously unknown state or process is termed nonantecedent (from the Latin, *non* [not] *ante* [before] *cedere* [go]). Since the initial onset of the First Industrial Revolution, there have been two additional revolutions, and we are now in the Fourth Industrial Revolution (Bianchi & Labory, 2018). The previous revolutions have resulted in both benefits and problems for society and the environment. For example, while providing industrial goods and services, increases in acid deposition, ground-level ozone, dichlorodiphenyltrichloroethane (DDT), and heavy metals such as lead have been linked to changes in the structure and function of both fauna and flora (Paoletti et al., 2010). Now, the Earth's climate is changing faster than at any other time in recorded history (IPCC, 2021). Therefore, global, regional, and local climate trends and variability are likely the most impactful environmental drivers in human history (IPCC, 2021). Climate change has already been responsible for directly modifying the duration and intensity of many natural phenomena, including droughts, floods, cyclones, and air temperature fluctuations (IPCC, 2021). Indirectly, climate change has been associated with changes in species (both native and invasive) abundance and diversity, wildfire risk, insect and disease occurrence, sea-level rise, and ice storm distribution, among other impacts (IPCC, 2021).

There are many questions regarding the extent, location, speed, and timing of these changes on the environment and humans (IPCC, 2021). Thousands of scientific papers are written yearly addressing many of these questions (Schmid-Petri, Adam, Schmucki, & Häussler, 2015). There remain, however, questions for which there are no answers because, as a society, we do not know what questions to ask. Therefore, being able to anticipate and plan for the unexpected is critically important to current and future forest health, and will be the focus of this chapter.

The peppered month case represented an unknown, unique, and innocuous event. However, not all unknown nonantecedent events (UNAEs) are harmless. During a United States Department of Defense (US DoD) news briefing on

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February 12, 2002, then-Secretary of Defense Donald Rumsfeld was asked about the lack of evidence linking the Iraq government with terrorist groups. In response, Rumsfeld discussed the potential for an unknown unknown threat. “There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don’t know. But there are also unknown unknowns. There are things we don’t know we don’t know” (Rumsfeld, 2011). This quote was mocked by many of the news media for making what many believed to be a nonsensical statement (Ezard, 2003). However, the statement was profound in illustrating the complexity and potential seriousness of an unknown nonantecedent threat.

Unknowns are common. The whole premise of the scientific method is designed to convert unknowns into knowns. However, Rumsfeld was not referring to an unknown but rather to a situation where there is no basis to formulate a threat (i.e., an unknown unknown). Therefore there would be no basis for searching for answers to the question, nor how the threat could be addressed. An unknown unknown has never previously occurred nor been imagined. These are the unknown unknowns of which Rumsfeld spoke. Although not as often quoted, Rumsfeld said during the same news conference that the unknown unknowns are the most critical questions to identify and answer because those are the situations, we are least prepared to address (Rumsfeld, 2002).

In the book “The Black Swan,” Taleb (2010) partially addresses the premise outlined by Rumsfeld which he referred to as known unknowns (as foreseeable but unknown, wildcard events or Black Swans). These rare outliers extend beyond anything that society has previously observed and may have extreme impacts. However, these black swans are very different from an unknown unknown in much the same way that a black swan is different from an orange swan. A black swan may be rare, but an orange swan is impossible based on current knowledge and, therefore, beyond the realm of consideration (i.e., an unknown, unknown).

The combination of the potential for an extreme impact and a lack of preparedness makes unknown unknowns exceptionally problematic. This issue may be most clearly illustrated regarding climate change. Climate change creates more frequent and severe disturbances that require society to update its collective adaptation knowledge base (IPCC, 2021). As with Rumsfeld’s unknown unknown terrorist threat, an improved understanding of the factors controlling the risk of an unknown unknown event is the first step in developing a plan to address potential negative event impacts. The only way to study an unknown unknown, or as we will term the condition in this chapter, an UNAE is by analyzing previous UNAEs, with the goal of discerning patterns that could be used to predict future UNAEs and their potential impacts on forest ecosystems. Ilmola and Rovenskaya (2016) used agent-based modeling (ABM), to identify and explore emergent phenomena in several fields (e.g., business, the social sciences, epidemiology, the military, law enforcement). Ilmola and Rovenskaya used ABM to simulate what could happen to a system when it is subjected to extreme “shock scenarios.” This approach yielded some surprising outcomes, such as a total collapse of regional economies in one simulation. Models are often a preferred option for studying “what if” scenarios to prepare for their potential actual occurrence.

The following three sections are designed to illustrate how patterns control UNAEs. First, we will define the terms used to assess previous UNAEs. Second, we will examine three ecological case studies where UNAEs were observed using the developed definitions. Finally, we will create a risk scale for predicting future forest UNAEs based on the factor patterns. However, this scale will not determine the exact nature of a future UNAE. Still, it could guide where and when a UNAE might occur based on the variables’ temporal and spatial distribution, creating the potential for an UNAE. This guidance may allow forest managers to more intensively monitor and better understand how different factors contribute to UNAE to transform potential unknown unknown forest impacts into known unknown forest impacts that can be studied and potentially mitigated before they occur.

Defining scales of knowledge

This chapter introduces new concepts and definitions for assessing potential future impacts on forest ecosystems. We will begin by more fully qualifying the four states of knowledge. Rumsfeld’s unknown unknown statement (Rumsfeld, 2002) is sometimes mistakenly referred to as being part of a Johari Window. The Johari Window was created by psychologists Joseph Luft and Harrington Ingham as a heuristic exercise for self-help groups (Luft & Ingham, 1955) and used to describe four possible states of known between two entities (i.e., arena, blindspot, façade, unknown). However, Rumsfeld was not referring to a condition in which either party lacked knowledge but rather a condition in which one entity (in this case, the US DoD) did not know where, when, how, or even if a potential attack might occur. Therefore the threat was an unknown unknown.

The analogous term to a Johari Window for climate change impacts on forests could be termed information and concept. It is essential to understand the concept of drivers and the information regarding those concepts to understand a situation fully (e.g., disturbance, impact, stress). The concept is the more important of the two knowledge components (i.e., concept and information). If knowledge regarding a forest impact is to be scaled from the unknowable to the knowable, then having both a concept and the data to test a concept is needed. A concept with no data could result in an unknown (e.g., a hypothesis to test). Having the data but no concept could result in an unknown unknown (as Rumsfeld described). Forest monitoring involves data collection. The use of this data is not always apparent at the time of collection. A lack of data and no basis for building a concept would produce an unknowable situation. These four degrees of concept and knowledge may thus be defined in a variation of the previously described Johari Window termed the Awareness Window as the Knowledge Window (Fig. 14.1).

Defining types of events

In addition to an UNAE, other terms must be defined to understand potential impact interactions fully. The case studies examined in this chapter will use hindsight to identify the environmental factors associated with nonantecedent events in three forest ecosystems. This study will then further examine how patterns of occurrence, variability, and trend could provide guidance for predicting climate change impacts that are currently not even anticipated (i.e., UNAE or unknown unknown).

Concept definitions

An antecedent event is a previously observed ecosystem impact. A nonantecedent event is a previously unobserved ecosystem impact. A nonantecedent event can be expected (i.e., expected nonantecedent event), such as the extirpation of red spruce from the southern United States due to climate warming. However, as described in the three case studies, a nonantecedent event can also be unexpected (i.e., UNAE).

Thus far, this chapter has defined the four degrees of awareness regarding our knowledge of a forest event occurrence (Fig. 14.1). The events do not occur at random. Regardless of whether an event is known or unknowable, predisposing factors contribute to the likelihood of an event occurring. In the case of a nonantecedent event, the interactions of factors responsible for creating the nonantecedent event (e.g., more co-dependent factor combinations, less data on which to develop a concept) become more complex. The data to predict an UNAE may exist, but there is insufficient understanding of the interactions on which to form a hypothesis or even randomly to search for correlations (i.e., a posteriori).

Ecosystems are complex, as are the interactions between ecosystem factors that trigger those events. Broadly, factors can also be divided into two categories: antecedent and nonantecedent. A nonantecedent factor has never been previously observed (e.g., soot in the Peppered Moth case). Likewise, an antecedent factor has been previously observed. Furthermore, a nonantecedent factor can be divided into either an unexpected nonantecedent factor or an expected nonantecedent factor. The three case studies were all unexpected, nonantecedent events before their occurrence. This combination of factors and events will form the basis of this chapter's discussion regarding future forest impacts throughout the chapter.

Forms of factor interactions to create events

Factors can trigger an event either individually or in combination. The case studies only examined multiple factor-caused events, but the following discussion will hypothesize other mechanisms for factors to create antecedent and nonantecedent events.

	Have Information	No Information
No Concept	Unknown Unknown	Unknowable
Have Concept	Known	Unknown

FIGURE 14.1 The four degrees of the Knowledge Window as defined by concept and information.

Single-factor triggers for a nonantecedent event

A single-factor nonantecedent event is the simplest to observe because these events do not include multiple covarying factors. There are two ways in which a single factor can trigger a nonantecedent event (Fig. 14.2). A trending nonantecedent factor may trigger a nonantecedent event (Fig. 14.2A). The increasing trend of greenhouse gases (primarily CO_2) is an example of a single trending factor causing a nonantecedent change in the global average decadal temperature (IPCC, 2021). Conversely, a single nontrending factor that remains within an antecedent range should never cause a nonantecedent event. However, a slow progression of change is not required to create a nonantecedent event if the factor includes a single extreme variance (Fig. 14.2B). For example, a single deviation in the average annual maximum asteroid size impacting the Earth likely caused the extinction of the dinosaurs at the end of the Cretaceous Age (Chiarenza et al., 2019). This example was a single, nontrending factor that caused a nonantecedent event during the Cretaceous Age.

Multiple factors trigger a nonantecedent event

Ecosystems are complex, and single-factor causations of nonantecedent events are rare (e.g., major asteroid impacts). As observed in the three case studies, multiple factors can be more challenging to predict, but they are more common. The following graphics illustrate how both trending and nontrending antecedent and nonantecedent factors can create a nonantecedent event.

The classic phrase "being at the wrong place at the wrong time" is an example of an antecedent factor creating a nonantecedent event. In this instance, two or more antecedent factors were brought together simultaneously to create a nonantecedent event (Fig. 14.3). For example, two bicycles cross an intersection at a right angle daily. No accident occurred either because they crossed at different times or because they were both alert when crossing the intersection to avoid an accident. However, one day they cross the intersection simultaneously while not paying attention, and an accident occurs (Fig. 14.3, red diamonds). Fig. 14.3 illustrates this condition by marking antecedent and nonantecedent events as the natural variability of independent factors that oscillate and occasionally align to create a nonantecedent

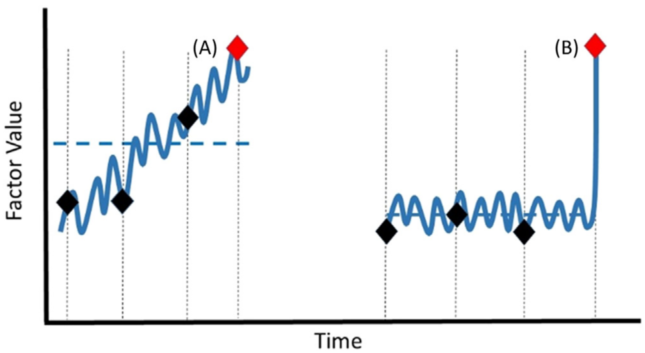

FIGURE 14.2 A single nonantecedent factor (nonantecedent factor) will likely cause an antecedent event (antecedent event, black diamonds (◆)). However, a nonantecedent factor can also cause a nonantecedent event (nonantecedent event, red diamonds (◆)) through either a trending variation (A) or a single extreme event (B). The horizontal dashed line denotes the factor average values. For illustration purposes, factor interactions are shown as discrete points in time (vertical black dotted line (- - ·)). In reality, the potential for an antecedent event or nonantecedent event to be caused by a factor(s) is a continuum.

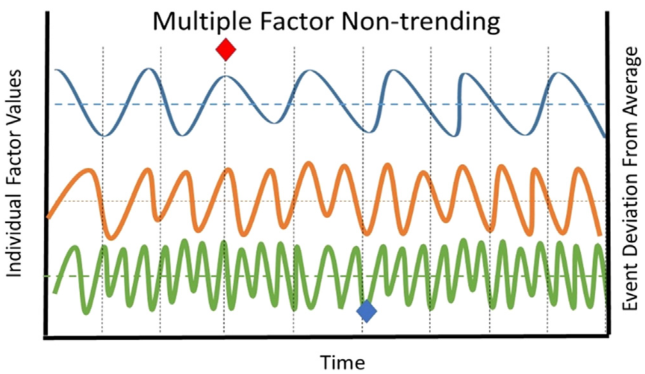

FIGURE 14.3 Multiple, nontrending antecedent factors (nonantecedent factors) will likely cause an antecedent event. However, nonantecedent factors can also cause a nonantecedent event (red diamonds (◆)) if they align in time and space. The three horizontal dashed lines denote each factor average value. The average of the three factors is denoted by the black dashed line. For illustration purposes, factor interactions are shown as discrete points in time (vertical black dotted line (- - ·)). In reality, the potential for an antecedent or nonantecedent event to be caused by a factor(s) can be either a continuum or an event.

event. In this case, the factors would be the time riders cross the intersection (orange and green lines) and their combined awareness factor (blue line) overtime.

The potential for a nonantecedent event increases as the factor variability or trend increases (i.e., the factor value moves further from an average state). If the trend or variability increases, the factor will eventually become nonantecedent. A nonantecedent factor does not necessarily translate into a nonantecedent event for two reasons. A nonantecedent factor may have occurred, but the factor does not have a sufficient impact to cause a nonantecedent event (Fig. 14.4, black diamonds). Also, as one nonantecedent factor increases in one direction, another factor (antecedent or nonantecedent) could be a trend in another direction to nullify a nonantecedent event (Fig. 14.5, green diamonds). For example, hot, dry, stagnant air is the optimal atmospheric condition for tropospheric ozone formation (Finlayson-Pitts & Pitts, 1993). McLaughlin, Nosal, Wullschleger, and Sun (2007) found that tropospheric ozone can damage foliage through open stomata. However, hot, dry air can draw down soil moisture resulting in the closing of leaf stomata. Thus the same air conditions that can create foliar damage (via ozone) can also protect the foliage (through stomatal closure). In this instance, a record hot, dry, stagnant air mass may not result in a record ozone impact event on the surrounding forests.

For this reason, the most significant risk of a nonantecedent event increases as the factor trends reinforce the deviation from the average event range of observations (Fig. 14.4). Conversely, suppose the factor variability and trend are moving in opposite directions. The condition (e.g., ecosystem structure or process) may appear more stable, but actually, the environment is becoming more volatile. Therefore it could result in a nonantecedent event if the factors align to reinforce a state change instead of canceling them out (Fig. 14.5, red diamonds).

Unknown, nonantecedent event forest case studies

A nonantecedent event can be highly disruptive to ecosystem structure and function, so a better understanding of the factors that trigger their occurrence is essential to future forest health. However, a nonantecedent event can (by defini-

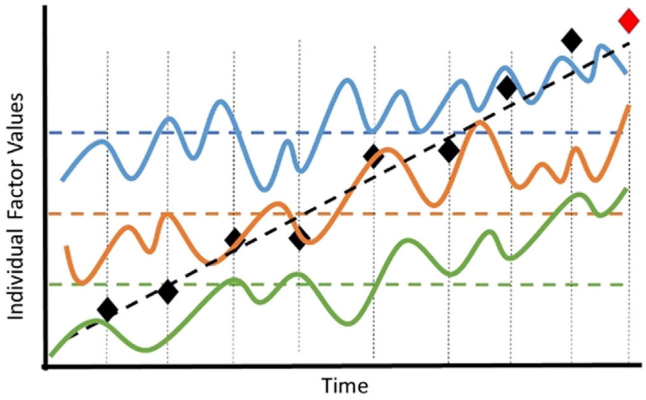

FIGURE 14.4 Multiple unidirectional positive trending antecedent factors (nonantecedent factors) will likely cause an antecedent event (antecedent event, black diamonds (◆)). However, nonantecedent factors can also cause a nonantecedent event (nonantecedent event, red diamond (◆)) through either a trending variation (A) or a single extreme event (B). The horizontal dashed line denotes the factor average values. The average of the factors is denoted by the black dashed line. For illustration purposes, factor interactions are shown as discrete points in time (vertical black dotted line (--·)). In reality, the potential for a factor to cause an antecedent or nonantecedent event is a continuum.

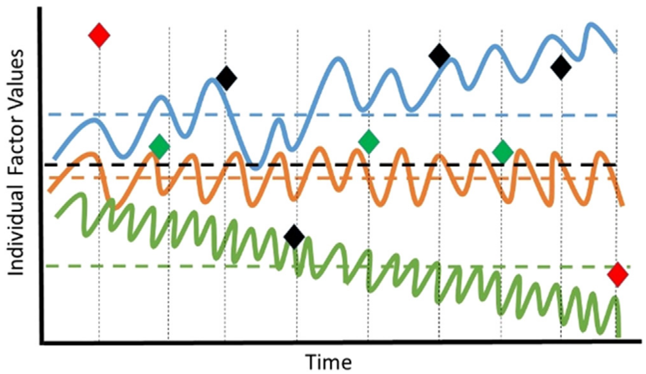

FIGURE 14.5 Multidirectional antecedent factors (nonantecedent factors) will likely cause an antecedent event (black diamonds ◆)). However, nonantecedent factors can also cause a nonantecedent event through either the alignment of factor variation (red diamonds (◆)) or false ecosystem stability (FES) through the offsetting (i.e., Misalignment) of factor variability (green diamonds (◆)). The horizontal dashed line denotes the factor average values. The average of the factors is denoted by the black dashed line. The vertical black dotted lines are sample points overtime of nonantecedent and antecedent events. For illustration purposes, factor interactions are shown as discrete points in time (vertical black dotted line (--·)). In reality, the potential for an antecedent event or nonantecedent event to be caused by a factor(s) is a continuum.

tion) only be nonantecedent once. Therefore researchers can effectively study the antecedent and previously nonantecedent factors after the event to predict when additional disturbances may occur.

Now that the terms and conditions of factors and events have been defined, three forest case studies of previously unknown nonantecedent events can be examined. These studies explain how antecedent and nonantecedent factors interact to create the four Known levels. The goal is to develop a concept of how the factors resulting in an unknown nonantecedent event occur so that this information could better predict future nonantecedent events. As each new environmental factor is added, the potential for the structure and function of an ecosystem to respond in a nonantecedent manner increases.

We examined three independent case studies (one from the United States and two from South Africa) to find a pattern within and between the studies that could be used to predict the possibility of future nonantecedent events better. Robust understanding and the capability to better predict the potential for a nonantecedent event could significantly increase land managers' and policymakers' ability to prevent or minimize negative ecosystem impacts.

Case study 1: South African case study on Prosopis

South Africa is prone to extreme events such as droughts, floods, and heatwaves. Severe droughts persist over several years and are often triggered by the El Niño Southern Oscillation (ENSO) because of the warming of the sea surface temperatures in the southern Pacific Ocean (Baudoin, Vogel, Nortje, & Naik, 2017).

Several species of Prosopis were introduced to the arid and semiarid Northern and Western Cape Provinces of South Africa (between the late 1800s and 1960s) to provide fodder, fuel, and shade during severe droughts (Harding & Bate, 1991; Shackleton, Le Maitre, Van Wilgen, & Richardson, 2015). Overtime, this species has become invasive, and stands of Prosopis covered approximately 1.8 million hectares (~1.5% of South Africa) by 2015, with an annual rate of spread between 3.5% and 8.0% of the existing area (Shackleton et al., 2015; van den Berg, 2010).

The invasion of Prosopis has many negative impacts on ecosystems, including the depletion of water resources (Dzikiti et al., 2013, 2017), loss of grazing land (Ndhlovu, Milton-Dean, & Esler, 2011), and effects on avian species through the loss of habitat (Dean, Anderson, Milton, & Anderson, 2002). In addition, keystone native vegetation such as *Vachellia erioloba* E. Mey, *Vachellia karroo*, and various grassland species are declining due to climate change, especially in ecosystems where they cooccur with Prosopis (Schachtschneider & February, 2013; Shackleton et al., 2015). The loss of the native vegetation has been attributed to the antecedent (e.g., droughts, wildfires, and human activities) and nonantecedent (e.g., habitat invasions) factors.

From 1982 to 1984, 1992–95, and 2015–17, severe droughts, often spanning multiple years, affected the entire southern African region (Baudoin et al., 2017). These droughts led to substantial loss of flora and fauna, but Prosopis were largely unaffected due to their resilience to harsh growing conditions. For example, Prosopis has been shown to outcompete native species such as *V. erioloba* with a similar root architecture for resources (Schachtschneider & February, 2013). The high mortality rate of *V. erioloba* in areas invaded by Prosopis in the Northern Cape was unexpected given that *V. erioloba* has a deeper root system ~ 70 m (Obakeng, 2007) compared to about 53 m for Prosopis (Canadell et al., 1996).

Average depth to the water table from 32 boreholes in the Schachtschneider and February (2013) study was about 56 m. The *V. erioloba* crown dieback rate was most severe in areas where Prosopis had a higher density, such as along ephemeral river channels, rather than in upland areas where the invasions were less dense. In a similar study by Shackleton et al. (2015), located in the Northern Cape, the basal area of Prosopis invasions was higher along perennial rivers than along ephemeral ones. This finding suggests that access to water impacted tree growth and that native woody species density, basal area, species richness, and diversity all decreased significantly as the basal area of Prosopis increased.

Access to deep groundwater alone does not seem to fully explain the ability of Prosopis to survive antecedent stresses while the native vegetation struggles to survive. The extended drought periods likely caused a drop in the groundwater level—but this should have impacted Prosopis more than the Vachellias due to Vachellias' deeper taproot (Obakeng, 2007). One possible adaptation strategy is that Prosopis roots may have a lower hydraulic resistance than native species, allowing rapid uptake of the receding groundwater during a drought. Another possibility, which is supported by Dzikiti et al. (2017), relates to the ability of Prosopis but not the native species, to manipulate soil and groundwater regimes as an adaptation strategy to survive periods of severe soil water deficit. Hydraulic redistribution was observed in Prosopis but not *V. karroo*. Also, the lateral roots of Prosopis ran very close to the soil surface and extended further from the tree stem (to scavenge for water and nutrients). Conversely, *V. karroo* roots were steeply inclined into the soil at 30°–45° from the surface. The root network of Prosopis allowed the development of a strong water potential gradient between the tap and lateral roots, such that when the taproot had groundwater access some of the water was deposited in shallow soil layers, resulting in higher soil water content in the root zone of Prosopis relative to *V. karroo* (Dzikiti et al., 2017). This condition supported the subsequent establishment of young Prosopis seedlings germinating from seeds produced in the vicinity of the root zone of the parent plant. Hydraulic redistribution has also been reported on Prosopis species in the United States by Hultine et al. (2006). Hydraulic redistribution affects the soil water content and enhances nutrient cycling and plant growth (Domec et al., 2010). Therefore hydraulic redistribution has implications for the propagation of species in arid environments where water stored in the shallow soil layers strongly influences the ability of young seedlings to survive droughts. Another antecedent stress that native vegetation may experience is the allelopathic effect associated with Prosopis, which releases chemical substances into the soil that act as growth inhibitors for other species.

This case study demonstrates that the invasive, alien Prosopis species successfully applied strategies to cope with antecedent stresses such as droughts. In contrast, the native species remained vulnerable, and that combination of antecedent and nonantecedent factors contributed to the nonantecedent event.

Case study 2: The Southern Cape and Tsitsikamma Wildfires

The winter rainfall region of South Africa experienced extreme drought from 2015 to 2018 with some arguing that area-dependent drought continued into 2019 (Archer et al., 2022). This area is a major agricultural producer in the country. Additionally, this is a site of sizable settlements, such as the City of Cape Town (Wolski, 2018). The southern Cape is the location of some of South Africa's commercial pine plantations, and the country's most extensive natural forest stands, predominantly comprising a belt of mixed evergreen Afro-temperate forest on the coastal platform (Geldenhuys, 1991). Areas of fire-prone indigenous sclerophyllous scrub (fynbos) vegetation flank the native forest patches, which are slow-growing and occur predominantly in fire-protected positions in the landscape (Geldenhuys, 1994). The fynbos extends into the more mountainous areas (Mucina & Rutherford, 2006) and is maintained as a dense but relatively low cover through regular burning (Fig. 14.6).

However, the established plantations of introduced tree species, favorable growing conditions (i.e., few native pests and diseases, wind-borne and fire-germinated seeds, high rainfall) combined with rapid growth rates, mean that extensive areas of fynbos have also been heavily invaded by alien tree species, including Australian acacias and eucalyptus, but most particularly pines (van Wilgen, 2015). These factors have substantially augmented above-ground woody biomass and fuel load and exacerbated fire risk (Kraaij, Arndt, Vhengani, & van Wilgen, 2018).

In 2017 and 2018, two catastrophic fire events occurred in this region. Although the area is prone to fires during the dry season (summer), these particular fires may be considered to be, to an extent, outside the norm [i.e., nonantecedent, given their proximity to winter and the shoulder seasons (as well as their intensity and extent)]. In early June 2017, the "Elandskraal and Kruisfontein" Fires decimated approximately 9440 ha in the vicinity of the towns of Knysna and

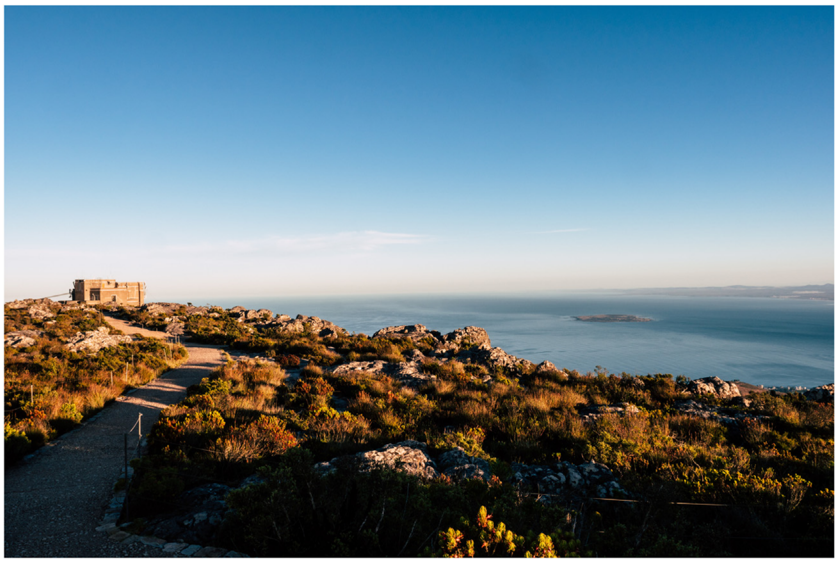

FIGURE 14.6 Fire-prone area near Cape Town, Western Cape, South Africa. *Photo by Tembela Bohle via Pexels.*

Plettenberg Bay (Frost et al., 2018), while the total area burned amounted to approximately 15,000 ha (Kraaij et al., 2018). In the period to follow, between late October and early November 2018, another severe wildfire event took place in this area resulting in damage to tree plantations amounting to 6800 ha in the southern Cape and 3700 ha in the Tsitsikamma area, while overall, the fire affected an area of more than 100,000 ha (Stehle, 2018).

The multiyear severe winter rainfall drought contributed to fire risk in these areas. Further, unseasonably high temperatures for that time of year increased the fire risk due to Berg winds. Berg winds are characterized by intense and persistent hot winds from the subcontinental interior that usually precedes an oncoming cold front as winds are directed offshore in the approach of a low-pressure system. In this wildfire event, Berg wind conditions were unseasonable and persistent (i.e., they did not diminish at night). As a result, the Knysna area experienced a severe wildfire in 2017 due to powerful dry winds, multiyear drought, and high temperatures.

Stehle (2018) observes that the Berg wind conditions were a significant contributing factor, with wildfires moving swiftly down a slope and burning old and very young vegetation. The analysis showed that the Berg winds resulted from a cold frontal system approaching the southwestern Cape during severe burn events. Persistent Berg wind conditions may be becoming more common, although this requires more study.

Case study 3: Southern Appalachian red spruce mortality

This case study was conducted in a forested area within the southern Appalachian Mountains in the Southeastern United States. High precipitation rates are generated as the warm, moist air from the Gulf of Mexico intersects with the western North Carolina Mountains (McNulty et al., 2019). Additionally, the mountain elevation keeps air temperatures low relative to other areas of the southeastern United States (McLaughlin et al., 2007). The combination of cooler air temperature and high annual precipitation rates create conditions allowing the red spruce (Picea rubens Sarg.) range to extend into the southeastern United States (Peters, Prasad, Matthews, & Iverson, 2020), including the area of Mount Mitchell State Park in western North Carolina. The Park was established in 1915 after the area had been heavily logged. However, logging has not been permitted within the Park since its establishment. Therefore most red spruce originated during the 1920s (McNulty, Boggs, & Sun, 2014). The forest has received minimal forest management over the past century (Fig. 14.7).

From 1950 to 1995, the National Oceanic and Atmospheric Administration National Center of Environmental Information (NOAA NCEI, 2022) cited that the area around Mount Mitchell had an average growing season air temperature of 13.2°C and averaged 650 mm of the average growing season (i.e., May–August) precipitation. However, from 1996 to 2000, a drought reduced the average growing season precipitation to 510 mm, and the average growing season air temperature increased to 15.2°C. The 1996–2000 period represented the most extreme fluctuation in climate for the last half of the 20th century for this area (NOAA NCEI, 2022).

The red spruce stands in this area were also subjected to additional stresses beyond elevated air temperature and drought. The southern Appalachian Mountains had been under chronic stress from ozone, nitrogen, and sulfur

FIGURE 14.7 Southern Appalachian Mountains in the southeastern United States receive nitrogen deposition, and occasionally droughts and southern pine beetle infestations. *Paul Brennan from Pixabay.*

deposition for decades (McLaughlin et al., 2007), which altered growth and forest health (McNulty et al., 2014). Finally, southern pine beetles (Dendroctonus frontalis Zimmermann) are an endemic pest of the southern United States that typically infest lower-elevation southern pine species (e.g., Pinus taeda). However, the hot air temperatures around Mount Mitchell between 1996 and 2000 allowed the predominately lower-elevation southern pine beetle to move into the temporarily warmer upper-elevation red spruce forest zone (McNulty et al., 2014).

Given this combination of elevated air temperature, drought, and southern pine beetles, red spruce began dying on Mount Mitchell in 2000. However, differences were observed between the red spruce killed and those that survived (McNulty et al., 2014) within the area. The suppressed trees had a lower mortality rate than dominant and codominant trees. In addition, the sites with the highest tree mortality had lower forest floor carbon-to-nitrogen (C:N) ratios. A low C:N ratio indicates high soil nitrogen fertility and high-growth potential (Vitousek & Howarth, 1991). This finding counters the prevailing understanding that dominant trees with larger crowns and root systems are less susceptible to environmental stress than suppressed, chronically stressed trees.

Field samples from the Southern Appalachian study suggested that the few surviving spruce areas with predominantly dead trees had higher foliar percent nitrogen (N) concentrations than those with low tree mortality rates (McNulty et al., 2014). Basal core samples from living and recently dead trees were measured for basal area growth and wood tissue isotopic carbon concentrations. The area where the beetles killed the dominant red spruce had higher long-term basal area growth rates and lower wood tissue isotopic C12 and C13 than the area with surviving trees (McNulty et al., 2014). The isotopic tree ring analysis indicated that the trees with the highest long-term growth rates were also the most chronically water-stressed and susceptible to drought despite their healthy appearance (McNulty et al., 2014).

In hindsight, the biometric and meteorological data suggest that a series of episodic nonantecedent factors (i.e., a three-year drought, abnormally high air temperatures, and the presence of the beetles) and chronic nonantecedent factors (i.e., elevated nitrogen deposition) combined to make the high growth rate trees much more susceptible to perturbation than would have been expected based on visual observations. McNulty et al. (2014) hypothesized that decreased soil C: N and long-term nitrogen deposition likely reduced the fast-growing spruce's root/shoot ratio (Aber, Nadelhoffer, Steudler, & Melillo,1989). This condition would not have typically stressed the trees, given that the area usually receives a high rainfall rate (McNulty & Boggs, 2010). However, as the drought developed, the reduced relative root biomass needed to supply the water coupled with the increased relative demand for water due to increased leaf area could have dried out the high-growth rate trees more than slower-growing, chronically stressed spruce. A lack of soil moisture has previously been cited to reduce tree oleoresin production and increase insect colonization (Mattson & Haack, 1987). The lack of tree resin in the high growth rate of trees would have allowed for southern pine beetle colonization and tree mortality.

Conversely, the slower growth rate trees (having a higher forest floor C:N ratio and lower foliar % N) did not experience the same level of insect-caused tree mortality. This difference suggests that under these extreme environmental conditions of high drought, the trees historically considered the most healthy and productive could be at higher risk than the slower-growing spruce. Spruce growing on poorer quality sites may have allocated proportionately more energy toward below-ground roots to fully utilize the limited existing water and nutrient resources, as found by Kleczewski, Herms, and Bonello (2012).

Drawing patterns from the case studies

The three case studies provide information on how a nonantecedent event's potential risk can change through trends and variability in both nonantecedent and antecedent factors as assessed based on the factor's trend and variability (Table 14.1). The trend rate can change overtime (e.g., the increasing global average air temperature rate during the 20th century, IPCC, 2021). Likewise, the variability can also change overtime. The interaction of trend and variability

TABLE 14.1 Antecedent (A) and nonantecedent (NA) factors were responsible for the nonantecedent events described by the three case studies.

Case study	Factor 1	Factor 2	Factor 3	Factor 4
Southern App. Red Spruce	Drought Heat (A)	1 Nitrogen Deposition (A)	2 Insects (A)	Landuse Practices (A)
Southern Cape Wildfires	3 Drought (NA)	4 Fuel load (NA)	5 *Alien* Sp. (NA)	6 Wind (A)
South Africa Prosopis	7 Drought (A)	8 Wildfire (A)	9 *Alien* Sp. (NA)	10 Landuse (A)

of single or multiple factors determines the potential for a nonantecedent event, as illustrated by the three case studies. Additionally, each nonantecedent event was also unknown unknown in that they were unexpected. While all unknown unknown events are antecedent, not all antecedent events are unknown unknowns. For example, if the sun went supernova (a nonantecedent event), all life on Earth would end (a known).

While the case studies illustrate how antecedent and nonantecedent factors interact to create nonantecedent events, these studies did not assess the importance of factor timing and extreme variation as triggers for nonantecedent events. Understanding how factor trends interact is essential for assessing the likelihood of a nonantecedent event occurring. In addition, understanding how multiple ecosystem factors interact at the extreme range of possibilities could guide unknown nonantecedent event potential risk.

Relationship between factors and events

The case studies illustrated that knowledge requires information (e.g., data) and a concept (a.k.a., a hypothesis) of how that data could relate to an event. In each case study, information regarding the nonantecedent event was either present or could be predicted before the nonantecedent event occurred. However, no one had predicted that the events would occur despite having the data. Understanding the factors that cause a nonantecedent event is essential for mitigation and recovery from potential negative impacts.

Each factor (e.g., temperature, insects, wildfire, drought) can be trending (positive, negative, or not at all [stable]), and variability (more, less, stable) controls on factor magnitude. Some factors (e.g., reduced precipitation and air temperature trends) may cancel each other out. In contrast, other factors may magnify each other (e.g., reduced precipitation and increased air temperature for wildfire risk). As each new factor is added, the potential for an ecosystem to respond in a nonantecedent manner increases. However, these are the unknowns. Nonantecedent events are not necessarily unpredictable. For example, wildfire behavior models could predict nonantecedent forest loss due to a nonantecedent drought. However, the potential for unknown unknowns (i.e., data exist, but not the concept of occurrence) poses the most significant risk to society and the environment.

Thus far, this chapter has focused on defining and identifying factors (i.e., antecedent and nonantecedent) that could contribute to developing a nonantecedent event. However, a more in-depth analysis of the individual and interacting factors is needed to gage the relative risk of event occurrence better.

One risk factor is increasing or high factor variability within the antecedent range (Fig. 14.2, red diamonds). When multiple factors' variability peaks and coincides, the risk of an antecedent event could increase considerably (Fig. 14.3, red diamond). Conversely, false ecosystem stability can occur if factor variability is high, but the factors are out of sync. False ecosystem stability is defined as antecedent factors with directionally opposite disturbance impacts. Combined, the factors cancel each other out to produce false, temporary stability (Fig. 14.3, blue diamond). For example, atmospheric ozone can damage stomatal guard cells, allowing more water transpiration from tree leaves (McLaughlin et al., 2007). Hot, dry weather is ideal for creating ozone that could be taken up through photosynthesis into leaves where cellular damage could occur. However, hot, dry weather can also create soil moisture stress, in which leaves lose turgor pressure and close, thus preventing ozone entry into the leaf. These offsetting environmental conditions create false ecosystem stability. As climate change creates more extreme fluctuation in climate across the region, including drought, the potential for factor alignments under extreme conditions increases. This example is analogous to a military arms race where balance may be maintained, but the potential for a nonantecedent event continues to increase, giving a false sense of security.

Therefore risk scenario development should include the combined impact of all known factors impacting an event as if they were temporally and spatially aligned at their point of maximum observed (i.e., antecedent) variability. Would this alignment create a nonantecedent event? Then the scenario should consider if the factors aligned and if their variability was even more significant. Finally, could this unobserved state of factors result in nonantecedent event even if that scenario has not been considered (i.e., unknown unknown)? For example, Thompson, Mackey, McNulty, and Mosseler (2009) hypothesized that climate change could result in "tipping point" changes where the ecosystem may change not only species but also ecosystem type (e.g., forest to savannah). The unknown of when, where, and how potential factors would drive these nonantecedent events qualifies them as unknown unknowns.

Monitoring as many factors as possible is necessary to predict a nonantecedent event from previously unrelated factor interactions if the risk of an unknown event is to be converted into an unknown event risk. Observing factor trends and variability, extrapolated values beyond the historically observed limits, and hypothetical factor combinations will provide the best opportunity to avoid unforeseen and extremely destructive climate change impacts.

The three case studies examined in this chapter had some commonalities and differences regarding developing their nonantecedent event. In two cases, antecedent and nonantecedent factors contributed to developing the nonantecedent event (Table 14.1). However, in the Southern Appalachian Case Study, a nonantecedent event occurred despite lacking even one nonantecedent factor. A series of antecedent factors (i.e., individually, previously observed) can create a nonantecedent event (i.e., collectively never previously observed). Therefore they could guide when and where a nonantecedent event may occur based on previously observed nonantecedent factors.

A single nonantecedent factor (such as an insect outbreak) is often cited as a cause of forest mortality. However, the outbreaks occurred for various environmental conditions that came together in an amplifying manner, as illustrated in Fig. 14.3. Examples of antecedent insect-caused tree mortality interacting with other antecedent factors include the mountain pine beetle (*Dendroctonus ponderosae*) caused mortality of lodgepole pine (*Pinus contorta*) in the Colorado Front Range (Mitton & Ferrenberg, 2012) and in British Columbia (Taylor, Carroll, Alfaro, & Safranyik, 2006); spruce beetle (*Dendroctonus rufipennis*) outbreak in Engelmann spruce (*Picea engelmannii*) from Alaska to Utah from 1987 to 2000 (Boucher & Mead, 2006); and bark beetle (*Ips, spp, Tonicus, spp*, and *Phaenopis, spp*.) outbreaks in central Europe in Scots pine (*Pinus sylvestris*) (Dobbertin et al., 2007). In these instances, insects have been episodically causing forest dieback since recorded history. A single factor can also become nonantecedent overtime regarding the frequency or the severity of the outbreaks, especially if the factor has a trending pattern, as expressed in Fig. 14.4.

Forecasting presently unknown future forest impacts

The three presented case studies were unique, but climate change is universal. As climate change progresses, forests are expected to experience an increase in the severity and duration of droughts, heat waves, and other chronic ecosystem stressors (IPCC, 2021). These environmental changes could convert currently nonchronically stressed forests into chronically stressed forests. Within each stress factor (e.g., temperature, insects, wildfire, drought), there can be trending (positive, negative, or none [stable]) and variable (more, less, stable) controls on factor magnitude. Some factors may cancel each other out (e.g., reduced precipitation and reduced air temperature trends), while others may magnify each other (e.g., reduced precipitation and increased air temperature). As ecological stress shifts occur, these forests could be at increased risk from biotic and abiotic extremes (i.e., a “tipping point”).These antecedent and nonantecedent factors that lead to nonantecedent events are tipping points where the relationship between cause-and-effect change. Rockstrom et al. (2009a, and, 2009b), proposed nine global-scale thresholds as Planetary Boundary Tipping Points. The nine boundaries included climate change thresholds, ocean acidification, stratospheric ozone, global nitrogen and phosphorus cycles, atmospheric aerosol loading, freshwater use, landuse change, biodiversity loss, and chemical pollution that collectively delimit “a safe operating space for humanity.” Some proposed boundaries were relatively simple to define because local inputs or changes make a predictable contribution to global processes with known thresholds. However, as presented in these three case studies, others (such as land-use change and biodiversity loss) are recognized as complex human system/ecosystem processes that are not readily associated with known global or continental thresholds.

A threat assessment guide

This chapter focused on detecting the potential for a UNAE caused by a combination of antecedent and nonantecedent factors. Therefore the challenge is to develop an approach that can allow for the assessment of these UNAFs to predict a UNAE. One such method was postulated by Markley (2015) using guided cognitive imagery and “mental time travel.” Markley proposed that imagination, creativity, and intuition could provide some guidance regarding UNAE risk. Markley (2015) stated that “It seems obvious that the use of rational/analytic modes of thinking alone are inadequate for research on alternative futures involving deeply systemic transformation. Intuitive methods that draw on “hidden reserves” of the mind are also needed.” This postulate may be true, but the tools to develop this mental resource are currently not available.

Another approach that may be relevant here was developed to identify wildcards affecting the future effects of climate change on biological systems, proposed by Srivastava et al. (2021). In this approach, the authors developed a framework to identify specific stress points where wildcards are likely to originate throughout the research process for studying the effects of climate change on biological systems.

As the rate, degree, and variability of climate change increase (IPCC, 2021), the potential for more severe and unexpected events could also increase. Some of these impacts may occur rapidly due to alignment driving factors. For example, Cook, Miller, and Seager (2009) cited how the alignment of historic drought and landuse change created the U.S. Midwest Dust Bowl in the 1930s, and the potential for such an event in the future is possible. The Dust Bowl was an example of an unknown nonantecedent event from which many lessons were learned and have become standard practice today. Conservation tillage, windbreaks, cover cropping, and other farming practices are all tools now used to prevent a reoccurrence of the Dust Bowl Years. However, trends and increasing variability in climate and other biological stresses (e.g., insects and disease) are creating new, unexpected levels of severity. Therefore the science of adaptation management must continue to evolve. The challenge will be to increase ecosystem resiliency to existing threats and increase resiliency to unknown threats using the risk identification system outlined in this chapter.

The antecedent and nonantecedent case study information from case studies summarized in Table 14.1 were used to develop a scale of increasing the likelihood of a nonantecedent event (Fig. 14.8). The figure examines the variabilities and trends of the factors that cause events. A trend is defined as the slope of the risk factor. Therefore a decreasing trend would mean that the slope decreases overtime. Likewise, a stable trend would have no slope, and an increasing trend would have an increasing slope overtime. As factor variability increases, more extreme conditions are possible. Each case study factor was either trending upward, or the variability of the factors was extreme when a nonantecedent event occurred. The lowest risk of a nonantecedent event is associated with decreasing factor trends overtime and little factor variability. Conversely, a factor with an increasing trend overtime and high variability is a prime variable causing a nonantecedent event (Fig. 14.6). Combining two or more high-risk factors further increases the possibility of a nonantecedent event.

Another approach that could be useful for identifying factors that could lead to a nonantecedent event was developed by Srivastava et al. (2021) to predict wildcards where affecting the future effects of climate change on biological systems, proposed by Srivastava et al. (2021). In this approach, the authors developed a framework to identify specific stress points where wildcards are likely to originate throughout the research process for studying the effects of climate change on biological systems. However, unlike the wildcard "joker" in a card deck, wildcards in the context of this chapter are often not individual ecological factors, but rather a combination of factors at various biotic and abiotic states that collectively become a wildcard. The complexity is further increased as state and interaction of the biotic and abiotic conditions change overtime.

Therefore without knowing how a series of nonantecedent factors could impact a forest, it is possible to estimate if a factor(s) will impact a forest in some previously unknown way. We outlined some of the critical components for determining how factors could be examined to guide how ecosystem monitoring and data trend analysis provide insight into understanding forecasts of potentially severe environmental threats that forests are not currently even imagined. As more nonantecedent events are recorded, additional patterns of previously unobserved factor interactions will occur. This additional knowledge will be essential to refine further the tools for methods in the quest to discover unknown unknowns before they cause societal or ecological damage.

Many studies suggest that the likelihood or severity of a UNAE can be reduced by building resilience. For example, Scheffer, Carpenter, Foley, Folke, and Walker (2001) reviewed catastrophic and unpredictable change in which ecosystems abruptly shift to a new state and concluded that "... building and maintaining resilience of desired ecosystem states is likely to be the most pragmatic and effective way to manage ecosystems in the face of increasing environmental change." However, the challenge is "resilience to what?" As illustrated in the case studies in this chapter, the disturbance factor may be very different in a UNAE event than it was a AE. This complex relationship makes developing ecosystem resilience very difficult when considering UNAFs.

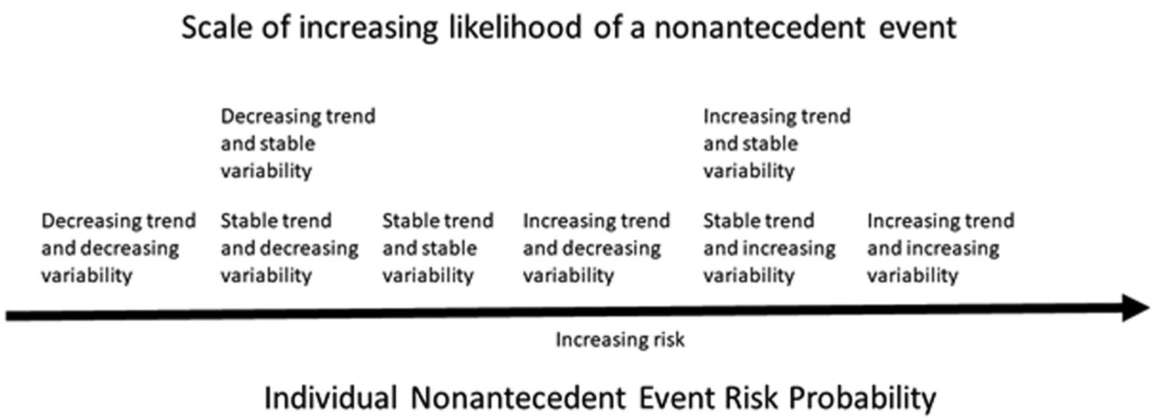

FIGURE 14.8 The relative risk associated with the event causing factor trends and variability.

The other chapters in *Future Forests* will examine how both multiple and individual biotic and abiotic factors impact ecosystem structure and function (including carbon sequestration, water resources, and recreation). However, as literate in this chapter, a fully examination of the unknown, unknown (i.e., wildcards, UNAFs) interactive impacts of climate change and other factors was beyond the scope of this work. As artificial intelligence (AI), supercomputing, and Monte-Carlo-type scenario development evolve, it will likely be possible (in the near future) to generate thousands of unique, previously unobserved ecosystem conditions and stresses. These databases could then be aligned using the methods of outlined in this chapter, with particular emphasis on discovering the amplification of individual factors (i.e., wildcards, UNAFs). AI could then be used to synthetically create the "mental imagery" postulated by Markley (2015), as a possible key to opening the realm of unimagined possibilities. The first documented case of a UNAE only resulted in insignificant shifts in moth coloration. Future UNAEs will almost certainly be much less benign.

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