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Article

Defective or Just Different? Predicting Storm Failure in Four Urban Tree Growth Patterns

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Abstract: Practitioners who assess the risk associated with urban trees often factor in the presence or absence of visual tree defects when determining whether a tree may fail. While these defects are a main fixture in many tree risk assessment systems and best management practices, the research supporting their usefulness in predicting tree failure during storms is limited. When looking at past research involving populations of storm-damaged trees, there are several defects that have never predicted failure (or have been associated with reduced rates of failure). In this study, we took a closer look at four such defects: codominant branches; branch unions with included bark; multiple stems originating from the same point; and overextended branches. After Hurricane Ian, we revisited 1519 risk assessed trees where one of these four defects was identified as the primary condition of concern. Fourteen of these trees experienced branch failure during the storm (which hit the study area as a downgraded tropical storm). Upon closer inspection, none of these failures occurred at the defect of concern. Our findings indicate that none of the defects assessed appeared to increase the likelihood of tree failure in the species tested. Our results are in line with past research on these defects derived from post-storm assessments and analysis.

Keywords: bifurcation; cyclone; forks; hurricane; tree biomechanics; tree risk assessment; typhoon

1. Introduction

Urban trees provide a wealth of environmental [1-2], social [3-6], and financial benefits [7-8]. However, they also pose a risk to people, property, and infrastructure when branches, stems, or whole trees fail [9]. Commercial, municipal, and utility arborists are often charged with determining which trees pose an unacceptable risk. Tree risk assessment involves assessing the likelihood of failure, the likelihood of impact, and the consequences of the impact on a target [10]. Initially, arborists typically rely on visual assessment methods when determining tree risk [11], although more sophisticated approaches are occasionally justified [12].

Previous studies have demonstrated the subjectivity associated with each component of risk assessment, including proximity to targets [13-14], observed structural weaknesses that increase likelihood of failure [15], and severity of consequences of impacting a target [16-17].

One aspect of tree risk assessment has received more experimental scrutiny than the others: assessing the likelihood of failure. Whether or not a tree fails depends on the loads it bears (drag, self-weight, weight of accumulated precipitation, loads associated

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with climbing and rigging, combinations of all of these) and the tree's load-bearing capacity. A key component of a tree's perceived load-bearing capacity is the presence of what arborists often refer to as "defects", which feature prominently in many risk assessment methods [10, 18-19]. Defects are structural weaknesses that result from natural processes (e.g., decay that forms after a branch breaks, growth of co-dominant stems, a split that forms following an intense loading event) and from management (e.g., decay that forms after pruning cuts or severed roots).

Because defects have been anecdotally associated with tree failures for many years, their effect on a tree's load-bearing capacity has often been tested. Many studies have relied on mechanical testing techniques to compare the load-bearing capacity of intact and defective trees or tree parts. For example, quasi-static pull tests have been used to assess the loss in load-bearing capacity associated with defects of the roots [20], trunk [21-23], and crown [24]. Analogous approaches have been used to investigate the loss in load-bearing capacity of codominant branch unions with [25-29] and without [26, 30-31] included bark. In these studies, the load-bearing capacity of codominant unions were compared to the load-bearing capacity of unions that include a plainly dominant stem and subordinate branch, as measured by their respective diameters.

Demonstrating the loss in load-bearing capacity associated with defects, however, only implies a greater likelihood of failure of structurally deficient trees. A related line of investigation has considered the explicit likelihood of failure of structurally deficient trees through post hoc observations of failed and standing trees following storms. Powerful analytical tools are sometimes used in such analyses [32-33], but simpler approaches such as proportion tests and logistic regression have also been used to detect failure patterns and investigate the effect of defects on likelihood of failure [15, 34-36].

Post hoc observational studies are more effective if trees have been previously inventoried [15, 36-37] for a number of reasons. First, cleanup begins immediately after a storm and some trees are removed before they can be assessed, reducing the sample that can be analyzed. Secondly, if the pre-storm inventory included a risk assessment, researchers can investigate its reliability of previous judgments. Lastly, without a record or previously identified visual defects for comparion, the prevalence and severity of defects hidden from view during the pre-storm inventory would go unreported.

To capitalize on the presence of municipal tree inventories that include risk assessment, which many communities have [11], it is necessary that (i) a storm of appropriate intensity affects the community within the timeframe specified in the risk assessment—typically one to three years [10]—and (ii) resources to conduct the post-storm assessment must be available. Using the Beaufort Scale for guidance, at wind speeds exceeding 74 km/h (the upper bound of Beaufort Scale 8), tree failure becomes widespread. Observations of failed and standing trees following storms of this or greater intensity might not provide useful data regarding the effect of defects on likelihood of tree failure.

Recent studies have indicated that likelihood of failure ratings assigned in tree risk assessments were reasonably correlated with standing and failed trees following storms [15, 36]. But the same studies also suggested that some defects anecdotally associated with likelihood of failure—codominant stems, branch unions with included bark, multiple branches originating from the same point, and overextended branches—were not statistically significant predictors of the likelihood of failure. Therefore, our objective for the study was to capitalize on an existing inventory, a timely storm event, and sufficient resources to survey standing and failed trees after the storm to investigate the effect of the four defects listed above on likelihood of failure.

2. Materials and Methods

2.1. Pre-storm Inventory

As part of a county-wide inventory in 2020, a team of three ISA Tree Risk Assessment Qualification (TRAQ) arborists conducted risk assessments of 10,917 trees in 144 parks in Hillsborough County, Florida, USA (USDA Hardiness Zones 9b, 10a). Arborists used the ISA BMP on Tree Risk Assessment [10] to conduct assessments on a five-year timeframe.

Unless otherwise noted, park users were assumed to be the primary target. Trees near built infrastructure or in maintained areas were assessed with a level 2 or "basic" assessment that involved visually inspecting the tree from a 360º perspective at ground level [10]. Trees growing in stands along the edges between maintained and more natural (unmaintained) areas were assessed with a level 1 or "limited visual" assessment, which is a rapid visual assessment from a single vantage point [10]. Such "edge trees" were only assessed if there were the potential that their failure would impact maintained areas. While trees could have multiple defects, the TRAQ arborists only recorded the primary defect of concern which would result in the highest risk rating in accordance with Smiley et al. [10]. Arborists also geolocated trees in the field using GPS and aerial imagery, identified trees to species, and measured their height and stem diameter 1.4 m above the ground ("DBH").

2.2. Storm Event

Hurricane Ian made landfall in Southwest Florida as a Category 4 storm on September 28th, 2022 [38]. The storm had sustained winds of 241 km/h as it reached the state, though the eye of the storm was 272 km south of our study area. Peak wind speeds of 98 km/h—"tropical storm" force according to the Saffir-Simpson Hurricane Scale [39]—were recorded in Tampa, Florida (the nearest weather station to our study area) [40].

2.3. Post-storm Assessment

We began the post-storm assessment on October 12th, 2022. Using our existing inventory data, we focused on a subset of the tree population that applied to our objective. We included in the subset only broadleaf angiosperms for which the risk assessment identified one of the following defects as the defect leading to the highest risk rating: codominant stems, included bark, multiple branches originating from same point, or overextended branches. From the subset of trees that met the previous two criteria, we excluded species with fewer than 15 individuals. We also excluded individuals from parks in which only a single individual met the three preceding criteria.

2.4. Data Analysis

Following the storm, we observed too few failed trees to conduct classical binomial tests or logistic regression. Instead, we present raw data in tabular form.

3. Results

Most of the trees assessed in this study were *Quercus virginiana* Mill. (66.3%; Figure 1). Our sample also included a significant number of *Quercus laurifolia* Michx. (10.9%) and *Ulmus alata* Michx. (8.4%). Eight other species made up lesser proportions of our post-storm assessment (3.4% or lower; Figure 1). Stem diameters in our sample ranged from 2.8 cm to 149.9 cm (Fig. 2). The average stem diameter was 41.3 cm. Tree heights ranged from 2.4 m to 26.7 m (Fig. 3). The average tree height was 11.1 m.

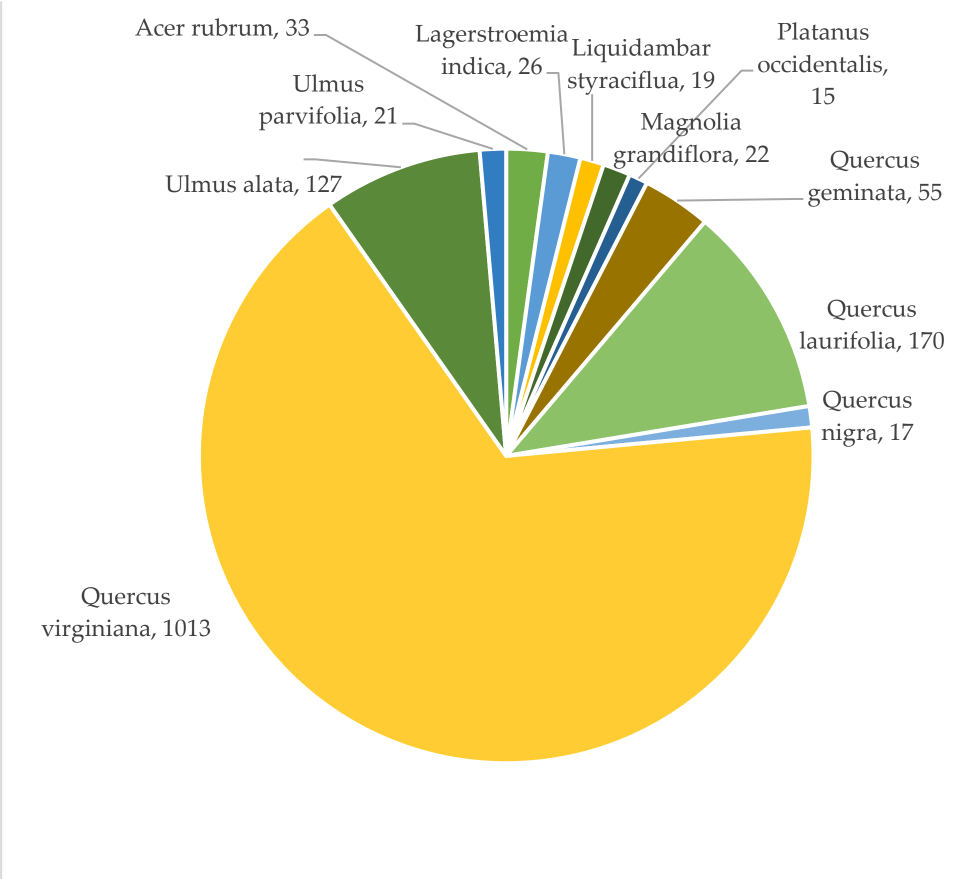

Figure 1. Species sampled in our post-storm assessment. Numbers represent counts (total n=1518).

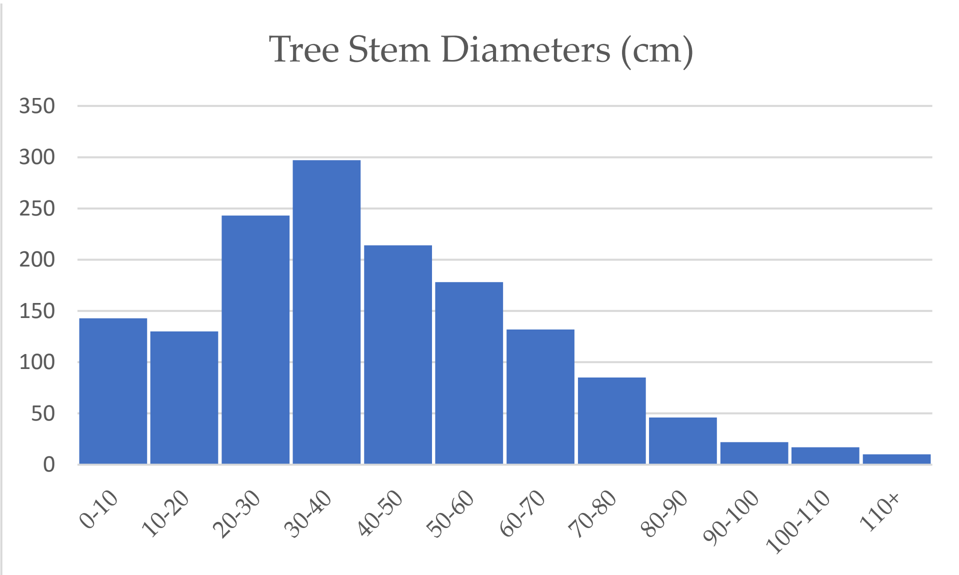

Figure 2. Histogram of stem diameters (cm) measured at 1.4 m for the 1518 trees reassessed after Hurricane Ian.

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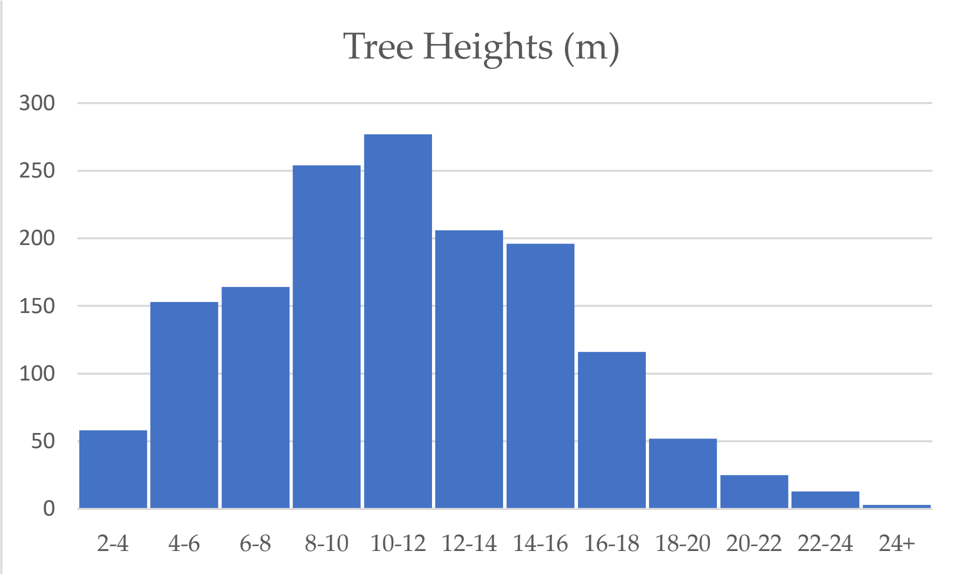

Figure 3. Histogram of tree heights (m) for the 1518 trees reassessed after Hurricane Ian.

Of 10,917 trees for which we originally assessed risk, 1,518 met our subset selection criteria. Within the subset, the defect associated with the highest risk rating was, in descending order of frequency, codominant stems, multiple branches originating from the same point, included bark, and overextended branches (Table 2). Only 14 trees (0.9% of the subset) failed during the storm; none of the failures occurred at the defect that we originally assessed as creating the highest risk rating (Table 2).

Table 1. Following exposure to tropical storm force winds associated with Hurricane Ian in September 2022, a count of standing and failed trees (n = 1,518) growing in 112 parks in Hillsborough County, Florida, USA that were assigned likelihood of failure ratings (in 2020) based on one of the following defects: codominant stems, multiple branches originating from the same point, and overextended branches.

Defect	Likelihood of Failure Rating	Standing	Failed[1]	Failed at Defect[2]
Codominant stems (n = 989)	Improbable	690	5	0
	Possible	283	3	0
	Probable	8	0	0
	Imminent	0	0	0
Multiple branches (n = 435)	Improbable	241	3	0
	Possible	184	3	0
	Probable	4	0	0
	Imminent	0	0	0
Included bark (n = 82)	Improbable	16	0	0
	Possible	60	0	0
	Probable	5	0	0
	Imminent	1	0	0
Overextended branches (n = 12)	Improbable	4	0	0
	Possible	8	0	0
	Probable	0	0	0
	Imminent	0	0	0

[1] Trees with any observed damage following the storm

[2] Trees with damage associated with one of the following defects: codominant stem, multiple branches originating from the same point, branch union with included bark, or overextended branch.

Most defects had been assigned likelihood of failure ratings of improbable (62.6%) or possible (35.3%) during the initial 2020 risk assessment (Table 1). Only 17 trees (1.1%) were rated as having a probable likelihood of failure rating, and a single tree with included bark (< 0.1%) was rated as having an imminent likelihood of failure (Table 1).

4. Discussion

The visual assessment of tree defects remains a key aspect of the tree risk assessment process. For example, Koeser et al. [41] showed that defect severity influenced a tree's risk rating more than proximity to a target and consequences of failure. The International Society of Arboriculture's (ISA) Tree Risk Assessment Manual [42], a common reference guide for practitioners, devotes a chapter to the relationship between defects (including those we considered in the current study) and likelihood of failure ratings.

Some of the relationships are based on destructive testing of excised branch unions that have shown the impact of diameter ratio [26, 43], branch orientation [44], included bark [25-26], attachment angle, and other morphological features on the load-bearing capacity of branch unions. However, more recent research has questioned whether codominant branch unions should actually be considered structural flaws – noting that their likelihood of failure depends on both the reduction in load-bearing capacity and the loads

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experienced [45]. This emerging narrative seems to be supported by models to predict the impact of the defects on storm-related tree failures.

Table 2 summarizes results of previous studies that, following a severe wind event, observed failed and standing trees with the defects we tracked in the current study. Table 2 also includes overall failure rates for two studies where trees without defects were included. In one [46], the failure rate for trees with defects was 3.1% greater than the failure rate of the trees without defects, a significant ($p = 0.038$) difference. But in the other study [35] the failure rate for trees with defects was 14% less than the failure rate of the trees without defects, also a significant ($p < 0.001$) difference. In both studies (and most studies in general), failures were quantified at the tree level. In any given tree, there will likely be a few defects and many more non-defective branches.

Compared to the studies listed in Table 2, failure rates for our study were noticeably lower, despite comparable peak wind speeds. This may be because we focused solely on tree defects that have failed to predict failures in previous studies. Additionally, it may be an artifact of the data collection methods. Both Koeser et al. [15] and Nelson et al. [36] analyzed datasets in which multiple defects of varying severity could have been linked to tree failure. In contrast, we analyzed a dataset that included only the most pressing defect as assessed before the storm. The failure rates observed in the current study align nicely with the likelihood of failure ratings assigned before the storm, most of which were "improbable" or "possible". Likelihood of failure ratings have been significant predictors of failure in past storms [15, 36] and include additional insights beyond the simple presence or absence of a particular defect.

Lower failure rates during the storm are supported by the comparatively small risk associated with tree failures in general [47]. This may appear misleading to practitioners who have observed many failures associated with defects such as those we studied. The lack of predictability offered by defects in this, and previous studies can be due to both fewer than expected failures (i.e., the majority of defects do not fail in storms) and the observation that some defects are quite common. For a larger perspective on likelihood of failure, we classified failure rates in this and previous studies according to likelihood categories of the Intergovernmental Panel on Climate Change ("IPCC") [48]. Even higher failure rates in Table 3 are considered "unlikely" in the IPCC's categories. A majority of the failure rates in Table 3 were categorized as "exceptionally unlikely" or "very unlikely".

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Table 2. Failure rates for trees with codominant stems, included bark, multiple branches originating from the same point, and overextended branches as reported in the tree risk assessment literature. The table also includes overall failure rates for all defective trees studied (including defects not listed above) and non-defective trees, where available.

Defect	Source[1]	Likelihood of Occurrence[2]		
		Exceptionally unlikely (0-1%)	**Very unlikely (0-10%)**	**Unlikely (0-33%)**
Codominant Stems	Koeser et al. 2020	-	9.8%	-
	Current study	0%	-	-
Included Bark	Gibbs and Greig, 1990	-	-	25.4%
	Koeser et al., 2020	-	5.4%	-
	Nelson et al., 2022	-	-	22.0%
	Current Study	0%	-	-
Multiple Branches	Koeser et al., 2020	-	4.9%	-
	Nelson et al., 2022	-	-	12.0%
	Current Study	0%	-	-
Overextended Branches	Koeser et al., 2020	-	-	25.8%
	Current Study	0%	-	-
All Defects	Gibbs and Greig, 1990	-	-	21.4%
	Kane, 2008	-	7.8%	
	Nelson et al., 2022	-	-	23.5%
	Current Study	0%	-	
No Defects	Gibbs and Greig, 1990	-	-	18.6%
	Kane, 2008	-	-	21.8%

[1] Wind speeds for each study: current study (98 km/h); two sites in Koeser et al., 2020 [15], (69 km/h, 85 km/h); Nelson et al. [36] (119 – 153 km/h); Kane [35] (162 km/h); Gibbs and Greig [46] (122 – 159 km/h).

[2] Terms from the Intergovernmental Panel on Climate Change [48].

Dunster et al. [42] include 33 defects or conditions conventionally associated with likelihood of failure (Table 3). For some, like decay, manipulative and post hoc studies have allowed the quantification of defect severity with an associated likelihood of failure rating. But for most of the listed defects and conditions, there are no post hoc assessments of failed and standing trees that support (or not) anecdotal evidence of their association with tree failure.

An advantage of identifying a wide range of defects and conditions for tree risk assessors to consider when assessing likelihood of failure is minimizing an assessor's exposure to liability. But there are also disadvantages, including increased effort required to document trees that have a defect (especially in settings where hundreds or thousands of trees are managed). Another disadvantage is to provide an opportunity for unscrupulous practitioners to circumvent local tree protection ordinances by claiming a safety exemption because a tree constitutes an unacceptable level of risk [49].

Table 3. Defects to assess and typical likelihood of failure (LoF) ratings within a three-year period, adapted from Dunster et al. [42], that have not yet been included in a post-storm assessment of failed and standing trees.

Defect	Three-year Likelihood of Failure Rating
Adventitious branches – Decay present	*Probable*
Adventitious branches – Holding wood present	*Improbable* to *Possible*
Adventitious branches – No decay present	*Possible*
Bows – Cracks present	*Probable* to *Imminent*
Bows – No cracks	*Possible* to *Probable*
Bulges	Not specified
Cankers	Not specified
Cracks – Compression	Not specified[z]
Cracks – Decay present	*Imminent*
Cracks – Freeze/Thaw	Not specified
Cracks – Frost	Not specified
Cracks – Horizontal	*Imminent*
Cracks – Multiple	*Probable* to *Imminent*
Cracks – No decay present	*Probable* to *Imminent*
Cracks – Shear plane	*Possible* to *Imminent*
Oozing	Not specified
Ridges	Not Specified
Seams	*Improbable* to *Probable*
Ridges	Not specified[1]

[1]Authors note that these may not impact likelihood of failure.

Given the disadvantages listed above and a lack of statistically significant correlations between defects and likelihood of storm-induced failure, it may worth considering a new term(s) to describe deviations from what practitioners think of as ideal tree form. The use of "defect" has its roots in traditional forestry, where it was used to describe conditions where a tree was weakened structurally or factors that reduced the quality and salability of the resulting timber products [50]. Some professionals already shy away from documenting "defects" in their consulting reports – opting instead for terms such as "attribute", "assessment feature", "condition", "feature", "mechanical constraint", "structural area of interest", and "tree risk feature" [51].

More research is clearly needed to support the current practice of tree risk assessment. Notable gaps remain with regard to what has actually been assessed in post-storm research efforts. And even defects that have been studied are limited to a few storm events. Future efforts should expand beyond the Southeastern United States to capture a wider range of species and storm conditions (i.e., derechos, ice storms, thunderstorms). Moreover, defects are often recorded as present or absent in industry forms and in the datasets that are derived from these documentation aids. While some defects are given very specific likelihood of failure ratings in industry guides, others are associated with a range of potential ratings. The latter scenario adds additional variability to modelling efforts, though this can be controlled somewhat with the addition of documented likelihood of failure ratings which have been used to predict failure [15].

5. Conclusions

While defects are a common fixture in our current risk assessment practices, the research surrounding their use remains limited and does not always support the assumption that they increase storm related failures. In particular, we were unable to detect a relationship between codominant stems, included bark, multiple branches emerging from one location, and overextended branches when we assessed storm damaged associated with Hurricane Ian in parks across the Tampa Bay (United States Area). More research is needed to assess if defects truly are defective. Moreover, use of the word defect should be reconsidered – especially given the lack of research surrounding many conditions noted in existing BMPs and training programs.

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