Dendroecology of Hurricanes and the Potential for Isotopic Reconstructions in Southeastern Texas

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1 Introduction

Hurricanes affect much of the lower to mid latitudes around the world. Hurricane season is during autumn when ocean waters have warmed from the summer, providing enough energy to maintain these large storms. Hurricanes cause severe damage when they make landfall with torrential rains and high wind speeds. Past occurrence of hurricanes can be documented through sediment analysis (Liu and Fearn 1993) but dendrochronological documentation of past hurricanes is a relatively new application that is just now being developed. This paper will present some recent research around the effects of Hurricane Rita and examine the potential for future dendrochronological reconstructions of hurricanes.

On September 24, 2005, Hurricane Rita made landfall approximately 50 km from the Big Thicket National Preserve in eastern Texas. As a category three hurricane, Rita made its way north along the Texas-Louisiana border. The path of the hurricane passed with 20 km of the Angelina National Forest. Hurricane Rita maintained at least a category one status until it was more than 150 km onto land. The Texas forest service estimated that the winds from Hurricane Rita damaged more than 3.8 billion board-feet of timber at an estimated value of $833 million dollars (Fig. 1).

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Fig. 1 Turkey Creek Unit showing trees downed by Hurricane Rita which made landfall on September 24, 2005 (Photo taken on December 13, 2005)

The Big Thicket National Preserve is an excellent location to study the effects of hurricanes on tree growth and to examine the potential for hurricane reconstruction. Between 1865 and 2007, 19 hurricanes passed within 100 km of the city of Kountze in southeastern Texas near our study areas (Fig. 2). Included in these 19 hurricanes are five which were category three or greater when reaching landfall. The most active period was a 25-year span from 1938 to 1963 which saw six hurricanes make landfall in this area. These hurricanes alter the structure of ecosystems by the removal of standing biomass, but they also bring large quantities of precipitation (albeit, for only a short duration).

Reconstructing hurricane events is difficult using standard dendrochronological techniques. However, a new technique may allow for high-resolution reconstruction of past hurricane events. Analyzing the $\delta^{18}O$ ratio of tree ring α-cellulose has proven a useful tool for characterizing hurricane events, and may provide pertinent information regarding hurricane frequency prior to instrumental records (Miller 2005; Miller et al. 2006).

In this paper we will present the results from a dendroecological analysis of the effects of Hurricane Rita. The current state of the art in dendrochronology has not provided robust reconstructions of past hurricane events, but ecological signals of past documented events are leading us to a clearer picture of the effect hurricanes have on succession in subtropical forests. Great potential exists for the use of stable isotopes to reconstruct past hurricane events and we will end with a discussion of the current state of that research and provide some suggestions on how to proceed with hurricane reconstructions.

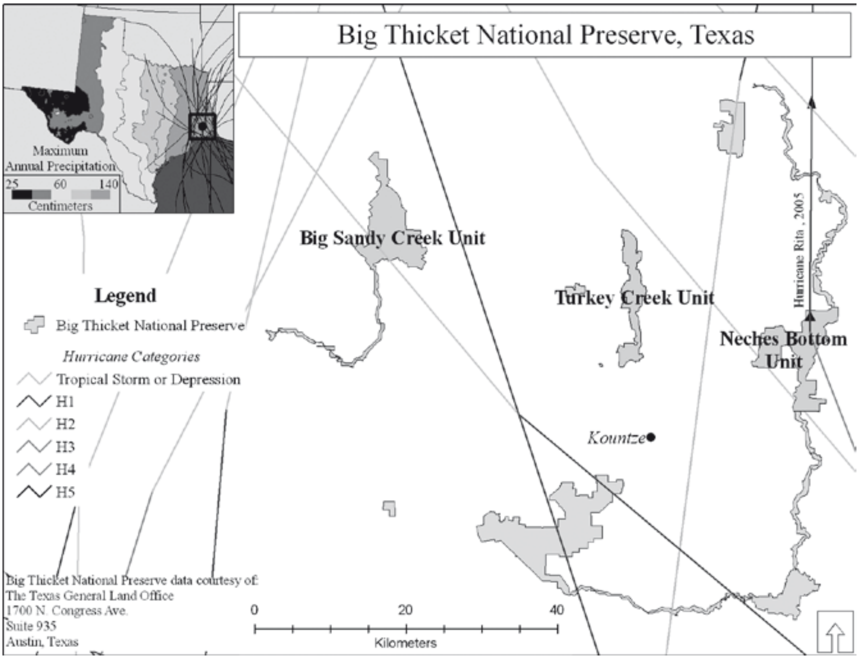

Fig. 2 Location of Big Thicket National Preserve sites with lines representing hurricane tracks and the hurricanes' category as it passed the field sites

2 Study Site

Established in 1974, the Big Thicket National Preserve has been an area of biological interest since Parks and Cory performed a biological survey in 1936. Numerous studies and surveys have been performed in and around the Big Thicket to measure vegetation dynamics (Harcombe and Marks 1977; Harcombe et al. 2002; Watson 2006). The Big Thicket National Preserve is comprised of 12 disjointed units that include the majority of the plant associations in this region. Because of this great biological diversity, the United Nations, Education, Scientific, and Cultural Organization (UNESCO) designated the 97,000 acre Big Thicket National Preserve as an International Biosphere Reserve in 1981.

Three units of the Big Thicket National Preserve (Turkey Creek, Neches Bottom, and Big Sandy Creek) were selected for this research. The Turkey Creek North site is dominated by Longleaf pine (*Pinus palustris*) and is situated on the Kirbyville-Niwana soil series (KgA). This series is located on nearly level (0–3% slopes with a 1% average) upland forest slopes. They are well to moderately well-drained with a seasonal water table of 0.6 m (UDSA SSURGO 2008). The elevations at the sampling site ranged from 42.0 to 42.6 m above sea level (a difference of 0.6 m) (Fig. 2). The Neches Bottom Unit, is at an elevation of only 9.1 m above sea level and a variability of less than 0.1 m, the site is seasonally inundated with water. These poorly drained soils have a forest canopy dominated by red maple

(*Acer rubrum*), american sweetgum (*Liquidambar styraciflua*), and oaks (*Quercus* spp.) on the slight upland flats, and by flood-resistant species such as Water tupelo (*Nyssa aquatic*) and bald cypress (*Taxodium distichum*) in the sloughs. The understory is a mix of shade-tolerant species such as ironwood (*Carpinus caroliniana*), pop ash (*Fraxinus caroliniana*), and holly (*Ilex* spp.) (Hall and Harcombe 2001). The Big Sandy Creek site is dominated by *P. palustris* and is located on Pinetucky fine sandy loam soils (PfB). The soils are well-drained with a seasonal water table of >2 m. Elevation at the sample site is approximately 75 m above sea level. All of these sites are relatively low-lying without much topographic variability and their proximity to the coast (approximately 100 km) makes them very susceptible to inundation from the heavy rains associated with hurricanes.

3 Material and Methods

3.1 Dendroecology

Dendroecological analyses were undertaken in order to identify an ecological signature for hurricane events and to determine if *P. palustris* is using meteoric precipitation as its primary source of water. Two projects were completed that can provide ecological information on the past occurrence of hurricanes. First we completed a stand-age analysis of two 20 × 20 m plots in the Neches Bottom Unit of the Big Thicket National Preserve to quantify changes in forest structure. All living and dead trees in the plots were sampled. The seven species dated in these two plots were *A. rubrum*, *F. caroliniana*, *N. aquatic*, American sycamore (*Platanus occidentalis*), *Q. lyrata*, *Q. nigra*, and *T. distichum*.

Second we selectively cored *P. palustris* trees in the Turkey Creek Unit of the Big Thicket National Preserve to determine their response to climate and see how hurricane events changed their response. Two increment cores were taken from each selected tree on opposite sides of the bole across the slope. One core was taken at breast height (approximately 140 cm above the forest floor) and the second was taken near the base (to maximize age) using an increment borer with a 5.15 mm interior core diameter. All cores and cross-sections were sanded with progressively finer grit sandpaper (ANSI 120-grit (105–125 μm) to ANSI 400-grit (20.6–23.6 μm)) and then hand sanded with up to 9 μm sanding film (Orvis and Grissino-Mayer 2002). All cores and cross-sections were visually cross-dated using a combination of skeleton plotting (Stokes and Smiley 1968) and memorization method (Douglass 1941) and each tree-ring was assigned to its exact year of formation.

After the cross-dating was complete, the individual rings from each sample were measured (earlywood (EWR), latewood (LWR), and total ring width (RWL)) using a Velmex measuring system with 0.001 mm precision. Measurements and cross dating were checked with the program COFECHA (Holmes 1983; Grissino-Mayer 2001). The EVENT program was used to perform a superposed epoch analysis examining the effect of drought and precipitation on the radial growth of *P. palustris*. This program compares one record (in this case radial growth) to the punctuated events that are defined by the user (in this case either drought years or hurricane events). Hurricane events were identified based on a hurricane track being within 92 km of Hardin County, Texas using data from the National Oceanic and Atmospheric Administration (NOAA), Coastal Services Center.

3.2 Dendroecological Results

Sites in the Turkey Creek Unit from the Big Thicket National Preserve on the Texas Gulf Coast had an interseries correlation of 0.587 demonstrating that these trees crossdate well. Using factor analysis of climate variables (precipitation, temperature, and drought), approximately 30% of the growth in *P. palustris* was explained by the previous year's evapotranspiration and current summer precipitation. These dry conditions could well be amplified in Texas due to the elevated summer temperatures combining with the lowest average monthly precipitation during the year (Fig. 3).

The superposed epoch analysis found a significant decrease in radial growth in the year of a drought in both the latewood and total ring width chronologies (Fig. 4). With regards to hurricane years, hurricane derived precipitation had a significantly positive effect on radial growth in the year of a hurricane in both the latewood and total ring-width chronologies (Gentry 2008).

This research also found that numerous trees of many different species had establishment dates in the Neches Bottom that coincided with historical hurricane events (Fig. 5). The majority of the establishment dates occurred during six separate hurricane events between 1879 and 1963. A large number of species (25.0%) established during hurricanes in 1949 and 1957 (Hurricane Audrey). The majority of the species identified in these establishment pulses were shade-tolerant or late successional species such as *A. rubrum*, *F. caroliniana*, and *T. distichum*.

In addition to the trees which had establishment dates coinciding with hurricane events, we were also able to identify increases in radial growth at the time of the hurricane where advanced regeneration was able to acquire canopy dominance after the hurricane removed many or most of the mature trees on the site (Fig. 5). The majority of these species were *A. rubrum* and *F. caroliniana*. None of the dated species which established the year of the hurricane or could be attributed to advanced regeneration were pioneer species.

3.3 Dendroecological Indicators of Past Hurricane Activity

Tree rings provide a biological proxy with annual (to sub-annual) resolution that has the ability to record changes in climatic patterns back centuries, even millennia.

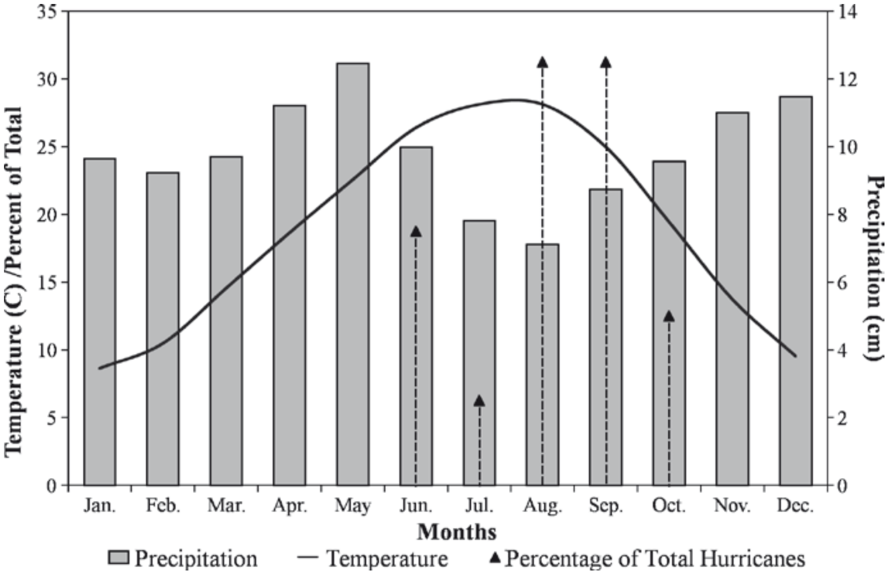

Fig. 3 Percentage of total hurricanes (*dotted arrows*) occurring by month compared to the Texas Climate Division 4 climograph. The Hurricane data is from NOAA for hurricanes that have tracked within 92 km of the field area

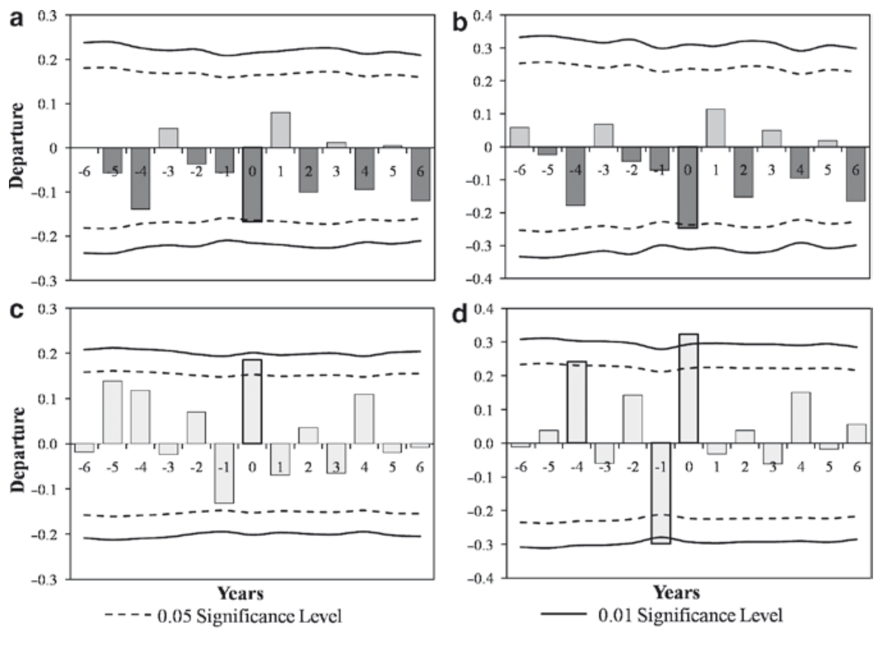

Fig. 4 Results from the superposed epoch analysis. Year zero represents drought years compared to radial growth in *Pinus palustris* as measured by total ring width (**a**) and latewood width (**b**). Figures **c** and **d** compare radial growth the year of a hurricane event with total ring width (**c**) and latewood width (**d**)

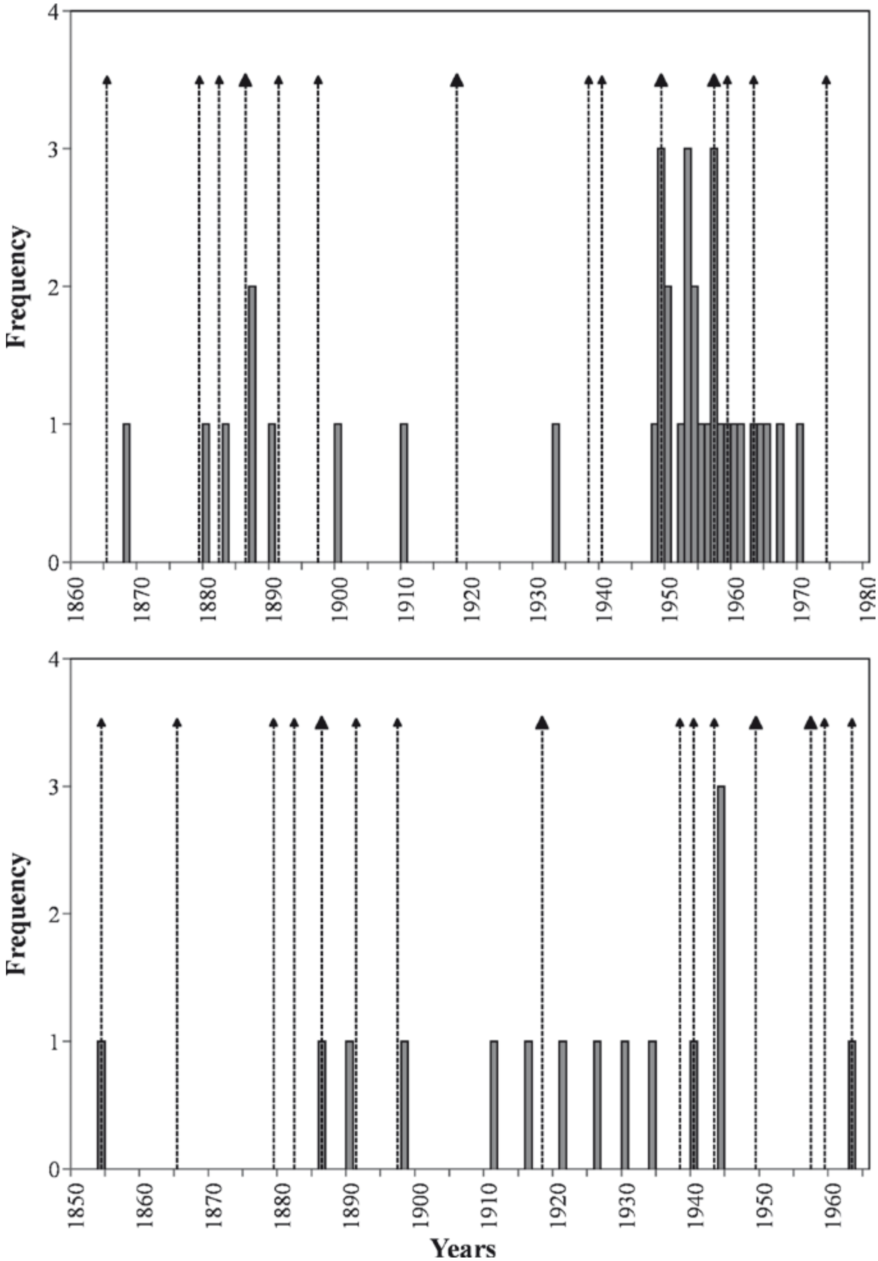

Fig. 5 Establishment dates for trees at Neches Bottom (*above*) and Weir Woods (*below*). The y-axis shows the number of trees that established in each year. The hurricanes events are marked with triangles along the top of each graph with stronger hurricanes denoted with a larger triangle. The differences in *shades of gray of the bars* represent the different species

The dendroecological study presented here documents the distinct response of species to hurricane events, where large trees are removed from the canopy and suppressed species in the understory usually grow to fill the gap. Shade-tolerant tree species usually thrive when the canopy is removed, because those trees have been surviving in the understory until the time when competition for light has been removed.

Foster and Brooks (2001) also found that summer precipitation is one of the primary factors controlling radial growth in *P. palustris*. They compared transitional to xeric sites and found that moisture parameters had a strong influence on tree growth. Overall, they found that 17.5% of the variance in growth patterns was explained by their climatic parameters (monthly temperature, monthly precipitation, mean monthly PDSI, and monthly flow) compared to our analysis that had 30% variance explained. Generally tree-ring growth in the southern Atlantic and Gulf Coastal Plain is slowed by summer moisture deficits and dry conditions (Cook et al. 1988). This is the time period when rains brought by hurricanes may greatly increase growth especially in the latewood of the trees. We hypothesize that this increase in latewood width along with an establishment pulse may be strong ecological indicators of past hurricane events. More studies on other sites should examine these indicators to determine their reliability in reconstructing past hurricane events.

Tree-ring oxygen isotope chronologies may have a greater potential to develop high-resolution hurricane records that may provide crucial information regarding the long-term variability of hurricane frequency prior to instrumental records.

3.4 The Potential Development of Hurricane Reconstructions from Stable Isotope Studies

Trees are useful candidates for stable isotopic analysis because they are stationary and record the environment at a given location over time. Trees obtain water primarily from soil moisture. Shallow-rooted conifers, such as *P. palustris*, primarily use soil moisture derived from meteoric precipitation rather than tapping into the water table (Anderson et al. 2002). A portion of the oxygen isotope signal in these trees will therefore reflect the oxygen isotopic composition of meteoric precipitation (Anderson et al. 1998; Roden et al. 2000; Anderson et al. 2002; Waterhouse et al. 2002; McCarroll and Loader 2004).

Tropical cyclone systems produce rainfall with an oxygen isotope signal 10–20‰ lower than normal precipitation (Gedzelman and Arnold 1994; Lawrence and Gedzelman 1996; Lawrence 1998). The influx of precipitation from tropical cyclone events will replace or mix with existing soil waters. Uptake and assimilation of these waters into tree-ring cellulose results in a lighter isotopic signature in the tree rings. The North Atlantic hurricane season generally lasts from June to November, generally coinciding with the latewood portion of the annual growth ring.

By separating each annual growth ring into its seasonal component, the ^{18}O-depleted rainfall events associated with tropical cyclones may be identified (Miller 2005; Miller et al. 2006).

Most researchers use the cellulose extraction methods outlined by Green (1963) with later modifications by Loader et al. (1997) for small-batch processing. New techniques are being developed that increase the speed of analysis enabling researches to include more replication from different samples and allow them to conduct their analysis with smaller quantities of wood. The oxygen isotope ratio of tree-ring α-cellulose can be rapidly analyzed using a continuous-flow isotope ratio mass spectrometer (IRMS). Cellulose samples are typically converted to CO gas using high-temperature degradation (pyrolysis). The oxygen isotope ratio ($\delta^{18}O$) is reported in per mil (‰) notation, where $\delta^{18}O = (R_{sample}/R_{standard} - 1) \times 1000$. Here, R_{sample} is the ratio of the rare isotope over the abundant isotope ($^{18}O/^{16}O$), and $R_{standard}$ is the standard (V-SMOW for oxygen).

Several potential problems exist when using stable oxygen isotopes in tree rings to characterize hurricanes. First, hurricanes are dynamic systems, and the magnitude of isotopic depletion may vary widely across a single storm (Lawrence et al. 2002; Gedzelman et al. 2003). Secondly, location and intensity of precipitation are variable inside the storm (Gedzelman et al. 2003), so that rainfall is not spread evenly across the affected area. These issues may have marked effects in the amount of depletion and amount of moisture received by trees during an event. If precipitation is not significantly depleted compared to normal meteoric precipitation, or if minimal rainfall is received, then the ^{18}O-depleted signal may not appear in the tree-ring cellulose.

The initial oxygen isotope composition of the soil water prior to a hurricane event may also influence the ability of trees to record the storm. Detailed analyses of the oxygen isotopic composition of hurricane rainwater have yet to identify the amount of precipitation required to sufficiently alter the $\delta^{18}O$ of existing soil moisture. Tang and Feng (2001) noted that depleted rainwaters from hurricane events can remain in the soil for several weeks following the event, but the initial soil moisture characteristics preceding the hurricane events were not noted. It is possible that drought events may enrich the soil water $\delta^{18}O$ such that it is impossible for the ^{18}O-depleted precipitation from a hurricane to alter the isotopic composition of the soil water significantly (Miller 2005; Miller et al. 2006).

Tree-ring isotope records of hurricane events are still few. The first record developed for the southeastern U.S. (Miller 2005; Miller et al. 2006) spanned 220 years using living and remnant *P. palustris* samples from southern Georgia. The resulting oxygen isotope series recorded all hurricanes in the area with only one false positive event when compared to instrumental hurricane track and precipitation data from 1940 to 1990. The record also highlighted periods of increased and decreased hurricane activity, likely tied to long-term ocean/atmospheric oscillations patterns known to affect Atlantic Basin hurricane frequency.

Similar techniques are currently being applied to develop long-term hurricane records from the Florida Gulf Coast (Pensacola), South Carolina (Sandy Island), and the Texas Gulf Coast (Big Thicket National Preserve, Big Sandy Creek Unit)

(Nelson 2008, Lewis unpublished data). These studies are not complete as of yet, but initial results indicate that trees in these areas are capable of yielding long-term hurricane chronologies, although 100% accuracy of the records is unlikely.

The combination of stable isotopic analysis with stand-age structure analysis may be able to provide confirmation of past hurricane events. Many different factors can cause establishment pulses in deciduous forests or an increase in late-wood thickness in *P. palustris*. But these changes, coupled with a significant decrease in stable isotopic composition are likely to only be due to a hurricane. Due to ongoing research in this area (see Grissino-Mayer et al. 2010, this volume), we expect these techniques to be strengthened so that dendrochronological hurricane reconstruction can become more common in the next 10 years.

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