Active Anti-erosion Protection Strategy in Tamarisk (*Tamarix aphylla*)

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Plants have numerous active protection strategies for adapting to complex and severe environments. These strategies provide endless inspiration for extending the service life of materials and machines. Tamarisk (*Tamarix aphylla*), a tree that thrives in raging sandstorm regions, has adapted to blustery conditions by evolving extremely effective and robust erosion resistant characteristics. However, the relationships among its surface cracks, internal histology and biomechanics, such as cracks, rings, cells, elasticity modulus and growth stress, which account for its erosion resistance, remain unclear. This present study reveals that the directionally eccentric growth rings of tamarisk, which are attributed to reduced stress and accelerated cell division, promote the formation of surface cracks. The windward rings are more extensive than the leeward side rings. The windward surfaces are more prone to cracks, which improves erosion resistance. Our data provide insight into the active protection strategy of the tamarisk against wind–sand erosion.

Results

Erosion test in the windward and leeward sides of tamarisk surface. To analyze the effect of wind and sand on the growth of tamarisk, the surface and internal erosion of tamarisk in the windward and leeward sides were compared. Figure 1a shows the surface erosion rates of the samples with different diameters after reaching their steady state. The erosion rates on the windward side were much lower than those on the leeward side of the tamarisk surface with different diameters. This result indicates that the windward side of tamarisk trees have...
greater erosion resistance against sandstorms. To study the erosion without the surface morphology, the erosion rates of the different internal positions of the tamarisk with a 14 mm diameter (S2 in Fig. 1a) were tested, as shown in Fig. 1b. The erosion rate of the transition zone (I2) was lowest and the erosion rate of the windward side (I1 zone) was considerably lower than that of the leeward side (I3 zone).

Surface crack and cross-sectional structure of tamarisk. The appearance and structure of tamarisk trunks were the result of environmental stimulation. Figure 2 shows the surface cracks of the windward and leeward sides of the tamarisk trunks and the corresponding cross-sectional microscopic structures. Cracks were absent in both the windward side and the leeward sides in the trunks with smaller diameters, as shown in the top and middle panels of Fig. 2a. The cracks in the windward appeared on the trunk that grew to a certain size (top panel in Fig. 2b), but the cracks on the leeward side were absent (middle panel in Fig. 2b). When the trunks grew to sufficient sizes, the quantity and size of the cracks in the windward side were greater and larger than those on the leeward side of the same position of the same trunk, as shown in the top and middle panels of Figs. 2c–2e.

The cross sections of the trunks with different diameters were eccentrically shaped, as shown in the bottom panel of Figs. 2a–2e. Tamarisk subjected to stimulation during growth developed narrower rings, producing very thin rings during dry years and thick rings during wet years. The eccentric growth of tamarisk was related to environmental stimulation. The pith or centre was far away from

Figure 1 | Erosion rates of the windward and leeward side surfaces of samples with different diameters and internal different positions. (a) (S1–S2) The diameters were approximately 8, 14, 24, 30, and 44 mm, respectively. (b) (I1–I3) The internal different positions with diameter 14 mm (S2).

Figure 2 | Surface crack and asymmetric radial cross-section. Panels (a)–(e) show the surface cracks of the windward and leeward side and the corresponding cross-sectional microscopic structures. The diameters of the samples were approximately 8, 14, 24, 30, and 44 mm, respectively. (a) Cracks were absent in both the windward side and the leeward side. (b) Cracks started to appear in the windward, but not in the leeward side. The number and size of the cracks gradually increased with increasing trunk diameter. The cracks in the windward side were larger and more numerous than those in the leeward side of the same trunk, respectively (c–e). The piths of tamarisk with different diameters were far away from wind direction, or windward side (bottom, a–e). Scale bars, 4 mm (a); 7 mm (b); 8 mm (c); 15 mm (d), and 22 mm (e).
the windward side. The rings in the windward side were significantly wider than those in the opposite side. The wider rings exhibited the same orientation, with multiple cracks.

Anatomical variations in the same growth ring were observed and investigated under a microscope. The cross-sectional cell structure in the windward side, the transition zone between the windward side and the leeward side, and the leeward side of the same ring are shown in Figs. 3a, 3b, 3c, 3d, and 3e, 3f, respectively. The transverse section reveals large vascular cells in the same ring were almost the same size between the windward side and the leeward side (Figs. 3a, 3c, and 3e). However, the large vascular cells in the windward side were healthier than those in the leeward side. The changes in cell number within the tissue directly demonstrated cell division. The partially enlarged photos show that the tiny vascular cells were uneven, round, oval, and strip (Figs. 3b, 3d and 3f). However, the sizes of the tiny vascular cell were similar between the windward side and the leeward side. Histologic observations indicated that the eccentric growth was dominated by cell division.

**Ring width and biomechanics in the cross sections.** The rings in the windward side were wider than their corresponding continuation in the leeward side (Fig. 4). The width of the windward side was about twice that of the leeward side. The ring widths of the windward or leeward side were different because the rings were affected differently by annual environmental conditions. Different years were subject to different environmental effects in the windward or leeward side.

Nanoindentation was used to study the biomechanics, modulus, hardness and stress of the tamarisk and understand the relationships among its surface morphology, internal structure, and biomechanics.

**Figure 3** | Anatomic observation of the cross section of samples in Fig. 2b. (a) Transverse section optical micrograph of tissues from the windward side. The red box was magnified (b) through scanning electron microscopy (SEM). (c) Transverse section optical micrograph of tissues from the transition zone between the windward side and the leeward side. The red box was magnified (d) through SEM. (e) Transverse section optical micrograph of the tissues from the leeward side within the same ring as the windward side specimen. The red box was magnified (f) through SEM. The insets on panels (b), (d), and (f) show highly magnified SEM micrographs of tiny vascular cells. The cell wall thickness remained unchanged. Ring width gradually deceased from the windward side to the leeward side. Scale bars, 500 µm (a), (c), and (e); 20 µm (b), (d), and (f); and 5 µm in the insets.

**Discussion**

Surface erosion caused by particles during the flow wear of particulates was reduced by the crack on the surface. Studies on the surface morphology of the carapace of the desert scorpion and the non-smooth surface morphology of ribs showed that the grooved surface has better erosion resistance than the non-grooved one. Grooves can enhance fluid turbulence, which leads to a change of the flow field around the groove surface and, subsequently, a change of the particle motion pattern. Some particles leave the surface along with air flow without impact, and these particles impact the surface if the surface is smooth. Therefore, the number of particles impacting the surface decreases. As a result of the decrease in flow velocity, the velocity of particles in the two-phase flow decreases as well. Rotating flow in the groove can absorb particle energy that is used for impacting and correspondingly reduces the energy used in impact. Based on the above mechanism of erosion resistance of the grooved surface, the grooved pattern, that is, the cracks on the surface of the tamarisk body, clearly contributes to erosion resistance.

According to the micro-cutting theory of Finnie, the erosion weight loss of the ductile material is directly proportional to the elastic modulus. Therefore, the windward side (internal, excluding...
bark) has better anti-erosion than the leeward side because the elastic modulus of the windward side is larger than that of the leeward side (Fig. 1b). High elastic modulus is another important reason for the erosion resistance in the tamarisk.

The tamarisk has high wind–sand erosion resistance. Meanwhile, wind–sand erosion affects the internal directional growth (eccentricity) of the tamarisk. In addition, the eccentric growth is caused by the fast cell division. Eccentric growth of trees is affected by external conditions, such as snow pressure, competition of adjacent trees, and topography, et al. In this study, vertical tamarisks were collected on a flat terrain to eliminate the influence of these factors. The eccentric growth of the tamarisk was observed for the entire cross-section or all the rings. However, the position of the maximum ring width does not always move in one particular direction. It appears to be distributed randomly in the cross-section (Fig. 6), though the directions are directed at the windward side. Wind–sand erosion occurring at exactly the same direction every time is impossible. In other words, wind–sand erosion does not occur at the same position of the tamarisk every time. Therefore, a deviation phenomenon occurs, such that the maximum width directions of the rings are different. We can speculate that the eccentric growth is caused by wind–sand erosion, which is well verified in the bottom panels of Fig. 2a. The sizes of the large or tiny vascular cell are the same in the windward and leeward sides. The internal asymmetric growth of the tamarisk is due to the quantity of large and small vascular cells. The number of cells in the windward side is greater than that in the leeward side. The number of cells is associated with the cell division rate; that is, the higher the cell division rate, the greater the number of cells. The directionality growth of the tamarisk is caused by fast cell division. That is, the eccentric growth of organization is caused by fast cell division.

Study the relationships among surface cracks, eccentric growth, and growth stress is important to understand the active protection strategy of the tamarisk. We proposed a potential mechanism to characterize the structure–function relationship in this self-adaptive process for wind–sand erosion. Figure 7 shows the relationships among surface cracks, ring eccentricity, and growth stress. Ring growth is symmetrical under normal growth conditions, as shown in Fig. 7a. The cell division rate of the cambium (the growth layer between the bark and the xylem) increases when tamarisk is under stimulation from the external environment. It subsequently produces thicker rings, and the surface growth stress simultaneously increases (Fig. 7b). The stimulated site grows the cracks under increasing growth stress (Fig. 7c). The cracks reduce the surface stress. The inner tissues are maintained under compression, but the outer tissues are under equivalent tension. In this case, growth anisotropy is dictated by the inner tissues, whereas the isotropic outer...
epidermal wall provides the major resistance to growth. Therefore, the surface stress is released because of the emergence of scars, which benefits rapid tamarisk growth. The leeward side exhibits slower growth than the normal one because the windward side undergoes rapid growth, which absorbs the majority of nutrients. The tamarisk growth rings exhibit asymmetric growth, and the growth and crack form at the same time (Fig. 7d). Consequently, the external and internal stresses attain equilibrium. Cracks form earlier on the windward bark because of the rapid development of the new bark. The structural elements undergo controlled orientation, which leads to anisotropy that matches traction adaptation to environment directions. This phenomenon also explains why the windward side stress initially increased and then decreased in Fig. 5c. The cracks promote stress reduction, in turn, promotes cell division. Cell division then promotes growth of eccentricity, which promotes the cracks. Specifically, the cracks in the windward side are larger and more numerous than those in the leeward side of the same trunk.

Our study explains that the tamarisk forms its surface morphology and elastic modulus with active protection itself through the use of wind–sand erosion, and verifies that wind–sand erosion promotes the growth and crack formation at the same time. The rings (L2) on the windward side are thicker than that on the leeward side (L1). The near–surface tensile stress is σ2 after wind–sand erosion, and σ0 is greater than σ1. The cracks are most likely to develop along the direction of the rapid growth. The surface tensile stress of the windward is reduced. The cambium has lower growth resistance; thus, its growth rate is higher. The surface stress is reduced by the presence of cracks, that is, the surface stress σ1 is greater than σ2. Growth and crack formation occur at the same time. The rings (L2) on the windward side are thicker than the new born rings (L0).

Methods

Sample collection. Tamarisk was collected in Baicheng City, Jilin Province, China (121°12′–124°22′ E; 44°13′–46°18′ N). The climate in Baicheng City is temperate continental monsoon in the Eurasian Centre. The average annual number of gale weather days is 24, and the average annual number of days with gale (less than grade 8) weather is 47. The annual average wind speed is up to 3.7 m/s. The zonal soil types include gray desert soil, sandy clay loam, and sand soil. The average annual prevailing wind direction is south–southwest.

None of the trees completely grew vertically. Therefore, the tamarisk samples that leaned slightly (<5° at the base of the tamarisk), were collected to analyze the relationship between ring growth and wind–sand direction. The different trunks were approximately 8 mm to 44 mm in diameter.

Erosion test. The erosion wear test system was designed to study erosion wear according to the American Society for Testing Materials (ASTM)–G76–83 standard. The erosion test samples were 20 mm long. Three samples were tested for the same diameter trunk. The samples were initially eroded for 2 min to reach the steady–state erosion, which avoided adverse effects and ensured the accuracy of the test results. Erosion weight loss data were recorded every 10 s. Table 1 lists the erosion wear test conditions. Erosion rate was defined as the weight loss per unit time and per unit projected area (g/mm²·s⁻¹).

Nanoindentation experiments. Residual stress is defined as the stress that remains in a material without the application of an external load. Nanoindentation (Nano Indenter G200, Agilent Technologies Inc.) deforms materials at a very small scale and allows the determination of residual stress at the macro/nanoscale. Nanoindentation was used to measure the residual stresses in tamarisk. The residual stress in the tamarisk cross sections were calculated using the load–displacement data obtained during indentation. During the nanoindentation tests, the Poisson’s ratio was set to 0.45, the peak hold time was 20 s, the strain rate was 0.1 s⁻¹, and the unload strain rate was 0.5 s⁻¹.

The samples used for the nanoindentation test were obtained from areas on the tamarisk surface with no cracks. Before the tests, the tamarisk cross section were

| Table 1 | Erosion wear test conditions |
|---|---|---|---|---|
| Erosion particles | Particle diameter (mesh) | Pressure of air compressor (MPa) | Mass flow rate (g/s) | Impact angle (°) |
| Quartz sand | 40–70 | 0.50–0.55 | 25 | 90 |

Figure 6 | Relationships among wind–sand erosion, eccentric growth, and tissue growth. Red arrows mark the position of maximum ring width. W₁max and W₁min are the widest and the narrowest of the first ring, respectively; W₂max and W₂min are the widest and the narrowest of the second ring, respectively. The directions of W₁max and W₂max are different. Blue arrows mark the vascular cells. The sizes of the large or tiny vascular cells in the windward and leeward sides are the same.

Figure 7 | Schematic diagram of the relationships among surface cracks, ring eccentricity, and growth stress. (a) Tamarisk grows symmetrically with no erosion. The yellow circle represents the cambium. The outer and inner parts are the cambium and xylem, respectively. The initial near–surface tensile stress in the bark is σ₀. (b) Tamarisk begins to grow after wind–sand erosion. The newborn ring on the windward side (L₀) is thicker than that on the leeward side (L₁). The near–surface tensile stress is σ₂ after wind–sand erosion, and σ₀ is greater than σ₁. (c) The cracks are most likely to develop along the direction of the rapid growth. The surface tensile stress of the windward is reduced. The cambium has lower growth resistance; thus, its growth rate is higher. The surface stress is reduced by the presence of cracks, that is, the surface stress σ₁ is greater than σ₂. (d) Growth and crack formation occur at the same time. The rings (L₂) on the windward side are thicker than the new born rings (L₀).
cleaned with ethanol (95%), dried at room temperature (25°C). Tamarisk sample was cut into 2 mm wide strip, as shown in the inset of Fig. 2a. Then it was inlaid into epoxy resin. The epoxy resin was cured at room temperature for 24 hours. The sample was cut and carefully polished to 2 mm thick sections. Given the porous surface, the imperforated or cellular region was considered to reflect the stress accurately and comprehensively.

Modulus, hardness, and residual stress were calculated from the measured indentation depth–load curve using the Oliver–Pharr and Suresh methods. The calculation of residual stress required a stress-free point as a reference. The hardness of different positions of the tamarisk interior was different. Meanwhile, indentation depth was larger or smaller under the action of stress than under the stress-free state. The nanoindentation depth parameter was set to 500 nm in the test. Considering the depth was larger or smaller under the action of stress than under the stress-free state.

Indentation load decreases due to the release of compressive residual stress at a fixed penetration depth. Indentation load increases due to the release of tensile residual stress at a fixed penetration depth. The unloading curve can be fully described by the gradient of the initial part of the curve. Thus, the area of contact $A$ can be obtained.

$$ S = \frac{dP}{dh} $$

(1)

$$ h_i = \frac{P_{max}}{S} $$

(2)

where $S$ is defined as the slope of the upper portion of the unloading curve during the initial stages of unloading (also called the contact stiffness), $P_{max}$ is the maximum load, $i$ is a constant that depends on the geometry of the indenter, $i = 0.75$ for the Berkovich triangular pyramid indenter, and $h_i$ is the amount of sink in.

$$ h_k = h_{max} - h_i $$

(3)

where $h_k$ is the depth along which contact is made between the indenter and the specimen, and $h_{max}$ is the maximum displacement.

$$ A = C_0 h^3_i + C_1 h_i + C_2 h^2_i + C_3 h^3_i + \ldots + C_n h^n_i $$

(4)

where $A$ is the contact area for the surfaces. The coefficients for the area function are $C_0 = 24.65, C_1 = 20.27, C_2 = 0.03536, C_3 = 0.9318, C_4 = 0.02827, C_5 = 0.03716, C_6 = 1.763, C_7 = 0.04102$, and $C_8 = 1.881.

$$ P_{avg} = \frac{P_{max}}{A} $$

(5)

where $P_{avg}$ is the average contact pressure. For the tensile residual stress

$$ \sigma_{RT} = \frac{P_{avg}}{A} \frac{A_s}{A} - 1 $$

(6)

For the compressive residual stress

$$ \sigma_{RC} = \left( 1 - \frac{A_s}{A} \right) \frac{P_{avg}}{A} \sin \frac{\pi}{2} $$

(7)

where $A/A_s$ is the area ratio, with and without residual stresses, and $\pi = 24.7°$ for the Berkovich triangular pyramid indenter.

Micrograph analysis

The transverse sections of the tamarisk stem were obtained using a hand sectioning method. The cross-section micrographs were observed under light microscopy (SteREO Discovery V12, Carl Zeiss). After gold coating, SEM micrograph analysis by the gradient of the initial part of the curve. Thus, the area of contact $A$ can be obtained.
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Author contributions
Z.W.H. and L.Q.R. designed the project and guided the research. Z.W.H., W.Y. and J.Q.Z. carried out the experiments and wrote the paper. S.C.N. collected samples. All authors contributed to the discussions.

Additional information
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