Spatial organization and correlation properties quantify structural changes on mesoscale of parenchymatous plant tissue

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The study of plant tissue parenchyma's intercellular air spaces contributes to the understanding of anatomy and physiology. This is challenging due to difficulty in making direct measurements of the pore space and the complex mosaic of parenchymatous tissue. The architectural complexity of pore space has shown that single geometrical measurements are not sufficient for characterization. The inhomogeneity of distribution depends not only on the percentage content of phase, but also on how the phase fills the space. The lacunarity morphometric, as multiscale measure, provides information about the distribution of gaps that correspond to degree of spatial organization in parenchyma. Additionally, modern theories have suggested strategies, where the focus has shifted from the study of averages and histograms to the study of patterns in data fluctuations. Detrended fluctuation analysis provides information on the correlation properties of the parenchyma at different spatial scales. The aim is to quantify (with the aid of the aforementioned metrics), the mesostructural changes—that occur from one cycle of freezing and thawing—in the void phase of pome fruit parenchymatous tissue, acquired with X-ray microcomputed tomography. Complex systems methods provide numerical indices and detailed insights regarding the freezing-induced modifications upon the arrangement of cells and voids. These structural changes have the potential to lead to physiological disorders. The work can further stimulate interest for the analysis of internal plant tissue structures coupled with other physico-chemical processes or phenomena.
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I. INTRODUCTION

The apple fruit cortex is mainly composed of the fleshy tissue of parenchyma cells permeated with vascular tissue and intercellular air spaces.[1] Parenchyma cell walls have a thin primary layer, with randomly distributed cellulose fibres reinforcing a matrix of hemicellulose, pectin, and glycoproteins.[2] The nanostructure of the cell walls differs for different apple cultivars in terms of cellulose diameter, crystallinity, and pectin content.[3] The cells immediately beneath the surface are small (approx. 50 μm), rounded, and randomly orientated. Progressing towards the center, there is a gradual increase in cell size until they reach a maximum diameter (approx. 200–250 μm) at approx. 5 mm from the surface. Cell size is not only determined genetically but also by the environment, crop load, and maturity.[4] The voids between apple parenchyma form an incompletely connected network; void spaces can be long and may stretch over several hundreds of μm in the tissue. These voids do not connect or split, but are surrounded by smaller individual voids without preferential direction.[5] Parenchyma cells may assume distinctive characteristics by accumulating specific kinds of substances, i.e., apple parenchyma cells store carbohydrates.[6] The study of parenchyma's intercellular air spaces has important applications since they are related to the understanding of anatomy and physiology.[7] Quantification may be challenging due to the difficulty in making direct measurements of the pore space and the complex anisotropic mosaic of the parenchyma tissue.[8] The first issue can be solved with X-ray μCT (micro-computed tomography), which determines reliably the architecture of opaque porous media at μm to sub-μm resolutions.[9,10] The second issue can be tackled by measuring the spatial organization and correlation properties of tissue patterns.

Spatial patterns may exhibit scale-dependent changes in structure and often are difficult to identify and describe.[11] Lacunarity, as a second order statistical measure, quantifies the relationship between neighboring objects/pixels,[12] explicitly characterizes spatial organization, and quantifies the degree of translational invariance.[13,14] It uses multiscale windowing for measuring the scale dependency of heterogeneity, thus characterizing the geometry of deterministic and random sets.[15] In essence, it measures how data fill the space,[16] enabling the parsimonious analyses of patterns: aspects of gaps distribution, presence of structures, homogeneity in gaps distribution, and random or self-similar behavior.[17] Lacunarity is sensitive to local aggregation or clustering and handles departures from stationarity.[18] In principle, lacunarity may seem similar to the concept of multifractals.[19] However, multifractals discern a globally consistent value based upon the singularity of local scaling exponents, whereas lacunarity defines the magnitude of local variations not as they scale outward from those localities, but rather between localities.[20]

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