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DOI
10.15302/J-LAF-1-020084

Publication date
2023

Document Version
Final published version

Published in
Landscape Architecture Frontiers

Citation (APA)
van der Velde, R., de Wit, S., & Pouderoijen, M. (2023). Cool Tree Architecture: A Descriptive Framework for a Tree Architecture Typology to Temper Urban Microclimates. *Landscape Architecture Frontiers*, *11*(5), 30-43. https://doi.org/10.15302/J-LAF-1-020084

https://doi.org/10.15302/J-LAF-1-020084 Received Date | 2022-11-26 Revised Date | 2023-07-21 Accepted Date | 2023-09-10

Cool Tree Architecture: A Descriptive Framework for a Tree Architecture Typology to Temper Urban Microclimates

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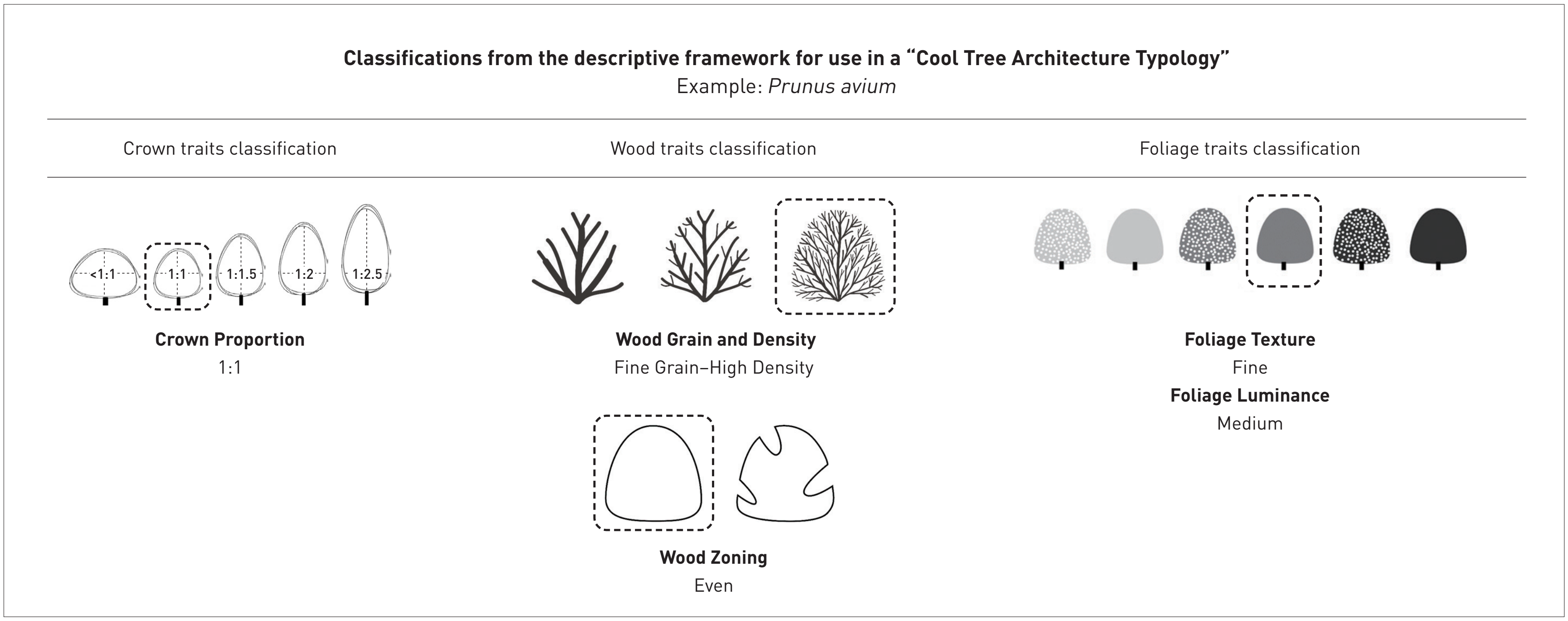
GRAPHICAL ABSTRACT



HIGHLIGHTS

- A descriptive framework to elaborate the architectural characteristics of tree species relevant to solar radiation reflectivity, absorptivity, and transmissivity
- Critical tree architecture classes for cooling including Crown Proportion, Wood Grain, Wood Density, Wood Zoning, Foliage Texture, and Foliage Luminance
- The descriptive framework can be used to develop a Cool Tree Architecture Typology to categorize trees based on common physical characteristics
- Tree architecture is a novel frame for developing metrics and standards of urban trees in relation to thermal microclimate amelioration

KEYWORDS

Tree Architecture;
Urban Heat Island;
Climate Adaptation;
Urban Microclimate Amelioration;
Cool Tree Architecture Typology

ABSTRACT

As the elementary unit of the urban forest, trees temper thermal extremes in urban microclimates through shading and evapotranspiration, and by altering the movement of air. Metrics on shade performances of different species, however, are currently limited, which can be remedied by the development of a method to describe the range of species and cultivars via a structured overview of physical characteristics impacting radiation reflectivity, absorptivity, and transmissivity. This paper proposes a descriptive framework based on the concept of "tree architecture," which has developed into a recognized field of plant study from the perspective of their physiognomy, morphology, and morphogenesis. The framework describes various architectural sub-traits within the overall trait categories of Crown, Wood, and Foliage. The descriptive framework can be used to develop a "Cool Tree Architecture Typology" (C-TAT), in which trees can be organized into similar types based on common physical characteristics. Further elaboration of sub-traits using observations of trees in controlled field laboratories resulted in new derivative classes for use as key in classifications for the C-TAT. The C-TAT can be used to organize the many species and cultivars occurring in, for example, Cfb Atlantic climate zone cities, to a lesser number of architectural types. This allows for more rapid evaluation and cooling performance calculations of tree inventories and can also be of value in assisting tree managers to propose more accurate thermal performance standards for trees in urban projects. The elaboration of tree architecture from an urban microclimate perspective complements existing elaborations and approaches in the field of tree architecture.

EDITED BY Tina TIAN, Yuting GAO

1 Introduction

The consequences of climate change impact urban environments and communities in multiple ways, including rising temperatures and heat waves[1]. Climate change exacerbates the existing phenomenon of urban heat island (UHI), which together are projected to have increasingly harmful effects on aspects such as human health and water availability[2][3]. Changes to a city's morphology, the design of its buildings, and the materialization of its unbuilt spaces are ways to make cities better adapted to deal with climate change and UHI[4]. As a key part of urban space, urban green infrastructure (UGI) is seen as an effective way to adapt to climate change and associated heat stress[5]~[7]. UGI refers to a broad range of green spaces such as urban woodlands, urban parks, street trees, green roofs, and green facades[8]. The urban forest, understood as the mosaic of trees and associated vegetation growing in and around dense human settlements[9], can be seen as the backbone of UGI[10] and a key means to adapt cities to rising temperatures and heat stress[11].

As the elementary unit of the urban forest, trees temper thermal extremes in urban microclimates through shading, evapotranspiration, and by altering the movement of air[12]. Shading is the common term used for the characteristics of trees that affect the reflectivity, absorptivity, and transmissivity of solar radiation through the tree canopy, and ensuing radiant energy reaching objects and surfaces beneath them[13][14]. Shading performances of different species of street trees vary greatly, however, depending on their physical characteristics[15][16]. Insights into how these varying characteristics impact shading are currently limited, which can be remedied by the development of a method to describe and classify the various species and cultivars into groups via a structured overview of the physical characteristics impacting radiation reflection, absorption, and transmission. Such a descriptive framework may also then be used to develop a "Cool Tree Architecture Typology" (C-TAT), in which a large number of species and cultivars can be categorized into a lesser number of architectural types based on common physical characteristics. The C-TAT will allow for more rapid development of cooling performance metrics of many tree species and performance calculations of existing urban tree inventories, assisting tree managers to propose more accurate thermal performance standards for trees in urban development projects.

This paper focuses on trees in the temperate climate zone in Europe, or Cfb (temperate oceanic climate①) according to the Köppen–Geiger classification[17], with The Netherlands as case study country within this climate zone.

2 Research Design

The development of a descriptive framework builds on the concept of "tree architecture," which has its early beginnings in pre-Linnaean plant studies focused on plant form description. With the development of sexual classification in the Linnaean system, plant form was relegated to a minor role, but Johann Wolfgang von Goethe[18] revived interest in the topic. Goethe's work informed later classifications such as by Alexander von Humboldt and Aimé Bonpland[19], who elaborated for the first time the overall structure of a plant community based on vegetation types and physiognomic features. Following Humboldt and Bonpland's work, Christen Raunkiaer presented a system including seven life-form classes[20]. Important contributions also came in the field of landscape architecture, such as from James Rose who studied the form of temperate trees and grouped them by their shared forms and the influence of these forms on human experience in (designed) environments[21]. A complementary body of work appeared in tropical forestry study in the 1970s led by Francis Hallé, Roelof Oldeman, and Philip Tomlinson, who developed a woody-plant classification system based on morphological characteristics using the term "tree architecture"[22].

The foundational structure for the descriptive framework builds on the work around tree architecture, augmented by insights from the field of tree physiognomy[23][24], tree morphogenesis[25], and tree morphology[26]. Research on morphogenesis, morphology, and physiognomy is similar to tree architecture, which focuses on the general life form of plants and their inherent organizational characteristics. This review results in three basic trait categories of Crown, Wood, and Foliage with descriptive sub-categories including crown shape, trunk morphology, branch morphology, twig morphology, leaf size, leaf shape, leaf color, leaf thickness, leaf texture, and leaf orientation. To elaborate and develop these characteristics towards a preliminary set of critical sub-traits and C-TAT classes, a comparative visual analysis of benchmark botanical illustrations was carried out (Step One). This was followed by the validation and refinement of the framework aided by field observations in dedicated outdoor laboratories. The definitive framework is divided into a descriptive section on critical sub-traits using drawings, diagrams, and text descriptions, and a section elaborating C-TAT classes (Step Two). How to deal with growth dynamics of trees was also addressed in this step. The framework was trialled using *Prunus avium* as a sample tree of Cfb climate zone.

2.1 Step One: Comparative Analysis of Benchmark Botanical Illustrations

Compared with floral paintings which belong to the world of art and aesthetic appreciation, botanical illustrations are pictorial depictions of plant traits primarily for scientific purpose[27]. Botanical illustrations have a number of key characteristics which make them relevant for this research. First, they isolate and portray definitive physical characteristics of a tree through drawings, paintings or engravings, allowing for a detailed portrayal of the whole tree attributes with a minimum of unnecessary visual information. Second, they depict a tree as a living entity in its adult or mature growth stage, and invariably show multiple phenological phases and other aspects that could not appear in a single tree specimen at any one time due to temporal or situational variables. Third, they are based on detailed studies and recording of actual individual specimens, thus revealing the interactions between endogenous factors (the fundamental growth patterns of a tree) and exogenous factors (the specific environmental conditions of a location). Botanical illustrations do limit the impact of exogenous factors, however, by avoiding the use of specimens which grow in environments with limitations, or specimens that are overly damaged or pruned. As such, botanical illustrations can be said to depict a tree in its most ideal or "natural" state.

These considerations form the starting point of the elaboration of sub-traits in Crown, Wood, and Foliage for a particular tree species. The goal of the analysis was to distinguish various traits emerging from benchmark botanic illustrations which enable a comparative analysis and elaboration of sub-traits. Leading out from these considerations, the collections of botanical illustrations for this study and comparison were chosen based on the following criteria: 1) illustrations by professional/trained botanical illustrators, artists or architects; 2) the use of appropriate representation techniques; 3) the use of accurate elevation

① Cfb, referring to temperate oceanic climate, is the humid temperate climate sub-type, generally featuring cool summers and mild winters with a relatively narrow annual temperature range and few extremes of temperature (source: Ref. [17])

projections; 4) illustrations to scale; 5) the whole tree depictions based on specimens in ideal situations; 6) trees shown both with and without foliage (where relevant); and 7) depictions of adult or mature trees.

Two benchmark sets of illustrations published in the last ten years were chosen which meet these criteria: *The Architecture of Trees* (2019)[28] with illustrations by Cesare Leonardi and Franca Stagi, and *Illustrated Trees of Britain & Europe* (2013)[29] with illustrations by David More. The botanical illustrations by Leonardi and Stagi were drawn with pen and ink on transparent film and consisted of scaled, elevation views (both active and dormant seasons for deciduous trees) and illustrations of leaf traits at the leaf axis unit scale (Fig. 1). Over the years, Leonardi and Stagi expanded the number of illustrations based on specimen trees in Italy, England, France, Austria, Switzerland, Czechoslovakia, Mexico, and Guatemala. Their selection of trees includes less hardy species which may not always survive severe winters, but nevertheless grow in various parts of Europe[28]. The work of More forms part of a long-term project to develop a durable visual record of the tree species, varieties, and cultivars growing in the British Isles, Ireland, and north-western Europe. The selection of almost 2,000 trees in this volume includes less hardy species which can be found in most parts of Europe, but may not always survive continental winters. Although the plates are not as systematically scaled as the work of Leonardi and Stagi, the specimens are generally accompanied by a scaled feature such as a person or animal. Illustrations of trees in the active phase are invariably full color oil paintings with dormant phase depictions in pen and ink (Fig. 2). Illustrations of leaf, bud, flower, fruit, and bark traits are also included in many plates.

The 232 trees illustrated in *The Architecture of Trees* formed the basis for a first selection of illustrations to study and compare in this paper. A selection of 101 trees was made, leaving out species with evident negligible impact on urban microclimates, such as dwarf cultivars (Table 1). Sample illustrations of these species from both volumes were printed to scale for visual analysis.

2.1.1 Elaboration and Selection of Sub-Traits Specific to Crown

The various architectural characteristics emerging from the analysis and comparison of the (pairs of) illustrations include Shape, Proportion, Texture, and Luminance②[30]. From the analysis it was concluded that the sub-traits Proportion and Shape were specific to the trait set of "Crown," and that sub-traits Texture and Luminance were applicable to the trait set of "Foliage." In terms of Crown Proportion, it was found that all crowns in the sample illustrations could be categorized into groups based on the proportional ratio of crown width (measured at the point of maximum horizontal dimension of the crown) and crown height (measured at the point of maximum vertical dimension of the crown). Of the sample trees that were analysed and compared, five proportion groups were identified: < 1:1, 1:1, 1:1.5, 1:2, and > 1:2.5.

Crown Shape is a second important variable within each proportion group. In < 1:1 group, a sole new crown shape was

② Luminance describes the amount of light passing through, emitted from, or reflected by a particular area. It is measured photometrically by the luminous intensity per unit area of light travelling in a given direction. This study established luminance based on human visual perception of the (lightness of the) foliage in illustrations and photographic studies in field laboratories. The Munsell color system was used to establish degrees of lightness (termed "value" in colorimetry). The value system grades lightness from 1 to 10, with 1 the lightest and 10 the darkest. The two other properties in colorimetry include hue (basic color) and chroma (color intensity) (source: Ref. [30]).

1 © Cesare Leonardi and Franca Stagi, 2019, *The Architecture of Trees*, Chronicle Books LLC, San Francisco.

2 © Cesare Leonardi and Franca Stagi, 2019, *The Architecture of Trees*, Chronicle Books LLC, San Francisco.

1. Botanic Illustrations of *Acer platanoides*: summer profile, winter profile, and foliage (source: Ref. [28]).
2. Botanic Illustrations of *Acer platanoides*: summer profile, bark, and foliage (source: Ref. [29]).

Table 1: Selected tree species for analysis

Abies alba	*Arbutus unedo*	*Cornus florida*	*Fraxinus ornus*
Abies cephalonica	*Areca catechu*	*Corylus avellana*	*Ginkgo biloba*
Abies concolor	*Betula pendula*	*Corylus avellana* var. *contorta*	*Gleditsia triacanthos*
Abies nordmanniana	*Betula pubescens*	*Crataegus oxyacantha*	*Gymnocladus dioicus*
Abies pinsapo	*Broussonetia papyrifera*	*Cryptomeria japonica*	*Hippophae rhamnoides*
Acacia baileyana	*Carica papaya*	*Cryptomeria japonica* var. Globosa Nana	*Hyphaene thebaica*
Acer campestre	*Carpinus betulus*	*Cupressus arizonica*	*Ilex aquifolium*
Acer monspessulanum	*Carya ovata*	*Cupressus cashmeriana*	*Jacaranda ovalifolia*
Acer negundo	*Castanea sativa*	*Cupressus macrocarpa*	*Jubaea spectabilis*
Acer opalus	*Catalpa bignonioides*	*Cupressus sempervirens*	*Juglans nigra*
Acer palmatum	*Cedrela sinensis*	*Daphniphyllum macropodum*	*Juglans regia*
Acer palmatum var. *atropurpereum*	*Cedrus atlantica*	*Davidia involucrata*	*Juniperus chinensis*
Acer platanoides	*Cedrus atlantica* var. *glauca*	*Delonix regia*	*Juniperus communis*
Acer pseudoplatanus	*Cedrus deodara*	*Diospyros kaki*	*Kigelia pinnata*
Acer saccharinum	*Cedrus libani*	*Draecaena draco*	*Koelreuteria paniculata*
Adansonia digitata	*Ceiba pentandra*	*Elaeagnus angustifolia*	*Laburnum anagyroides*
Adenium namaquanum	*Ceratonia siliqua*	*Erythea armata*	*Lagerstroemia speciosa*
Aesculus carnea	*Cercis siliquastrum*	*Eucalyptus camaldulensis*	*Larix decidua*
Aesculus hippocastanum	*Cereus giganteus*	*Euphorbia abissina*	*Laurus nobilis*
Agave americana	*Chamaecyparis lawsoniana*	*Fagus sylvatica*	*Libocedrus decurrens*
Ailanthus altissima	*Chamaecyparis lawsoniana* var. *nidiformis*	*Fagus sylvatica* var. *asplenifolia*	*Liquidambar styraciflua*
Ailanthus altissima var. *erythrocarpa*	*Chamaecyparis obtusa*	*Fagus sylvatica* var. Atropurpurea Group	*Liriodendron tulipifera*
Albizzia julibrissin	*Chamaerops humilis*	*Fagus sylvatica* var. *pendula*	*Maclura pomifera*
Alnus glutinosa	*Chorisia insignis*	*Ficus bengalensis*	*Magnolia grandiflora*
Alnus incana	*Cinnamomum camphora*	*Ficus benjamina*	*Magnolia purpurea*
Alnus incana var. *pendula*	*Citrus sinensis*	*Ficus carica*	*Mangifera indica*
Aloe dichotama	*Cladrastis lutea*	*Ficus elastica*	*Melaleuca diosmifolia*
Araucaria araucana	*Clerodendrum trichotomum*	*Ficus sycomorus*	*Melia azedarach*
Araucaria bidwillii	*Cocos nucifera*	*Fraxinus excelsior*	*Mespilus germanica*
Araucaria brasiliensis	*Cornus controversa*	*Fraxinus excelsior* var. *pendula*	*Morus alba*

Continued

Table 1: Selected tree species for analysis

Morus alba var. *pendula*	*Pinus pinea*	*Quercus macrolepis*	*Sciadopitys verticillata*
Nolina longifolia	*Pinus strobus*	*Quercus palustris*	*Sequoiadendron giganteum*
Nyssa sylvatica	*Pinus sylvestris*	*Quercus petraea*	*Sequoia sempervirens*
Ochroma grandiflora	*Pistacia terebinthus*	*Quercus pubescens*	*Styphnolobium japonicum*
Olea europaea	*Pistacia vera*	*Quercus robur*	*Styphnolobium japonicum* var. *pendula*
Olea europaea var. *oleaster*	*Platanus occidentalis*	*Quercus robur* var. *pyramidalis*	*Sorbus aucuparia*
Opuntia ficus-indica	*Platanus orientalis*	*Quercus rubra*	*Sorbus domestica*
Osmanthus fragrans	*Populus alba*	*Quercus suber*	*Sorbus hybrida*
Ostrya carpinifolia	*Populus nigra*	*Quercus trojana*	*Sorbus hybrida* var. *pendula*
Pandanus utilis	*Populus nigra* var. *italica*	*Ravenala madagascariensis*	*Stelitzia augusta*
Parrotia persica	*Populus tremula*	*Rhizophera mangle*	*Tamarindus indica*
Paulownia imperialis	*Prunus amygdalus*	*Rhus typhina*	*Tamarix gallica*
Phillyrea latifolia	*Prunus avium*	*Robinia pseudoacacia*	*Taxodium distichum*
Phoenix canariensis	*Prunus cerisifera*	*Robinia pseudoacacia* var. *bessoniana*	*Taxus baccata*
Phoenix dactylifera	*Prunus cerasus*	*Robinia pseudoacacia* var. *monophylla*	*Taxus baccata* var. *fastigiata*
Photinia serrulata	*Prunus serrulata*	*Robinia pseudoacacia* var. *pyramidalis*	*Thuja plicata*
Picea breweriana	*Pseudotsuga douglasii*	*Roystonea regia*	*Tilia cordata*
Picea excelsa	*Pseudotsuga douglasii* var. *pendula*	*Sabal palmetto*	*Tilia platyphyllos*
Picea excelsa var. *pendula*	*Pterocarya fraxinifolia*	*Salix alba*	*Tilia tomentosa*
Picea omorica	*Puya raimondi*	*Salix babylonica*	*Tsuga canadensis*
Picea pungens var. glauca	*Pyrus communis*	*Salix caprea*	*Ulmus glabra*
Pinus canariensis	*Pyrus salicifolia*	*Salix caprea* var. *pendula*	*Ulmus glabra* var. *pendula*
Pinus cembra	*Quercus cerris*	*Salix daphnoides*	*Ulmus minor*
Pinus halapensis	*Quercus coccifera*	*Salix eleagnos*	*Washingtonia filifera*
Pinus montezumae	*Quercus coccinea*	*Salix matsudana* var. *tortuosa*	*Yucca brasiliensis*
Pinus mugo	*Quercus farnetto*	*Salix pentandra*	*Yucca brevifolia*
Pinus nigra ssp. *laricio*	*Quercus glauca*	*Salix triandra*	*Zelkova carpinifolia*
Pinus pinaster	*Quercus ilex*	*Sambucus nigra*	*Zelkova serrata*

NOTES

1. The species were source from Ref. [28], and the naming of species follows from the publication, and some nomenclature has since been revised.
2. The highlighted ones are the species selected for this study.

identified from the sample: Ovoid. In the 1:1 group, five new crown shapes were identified: Paraboloid, Irregular, Cylindrical, Spheroid, and Pyriform. In the 1:1.5 group, two new crown shapes were identified: Conical and Ellipsoid. No new crown forms were identified in the 1:2 and > 1:2.5 groups. It is noted that crown shapes are inter-related to the height of the widest point of the crown.

2.1.2 The Elaboration and Selection of Sub-Traits Specific to Wood

The analysis and comparison of the botanical illustrations of sample trees with respect to trunk, branches, and twigs resulted in the identification of several new sub-traits, including Bark Texture, Bark Color, Wood Grain (the relative thicknesses of trunk, branches, and twigs), Wood Density (the total area and concentration of wood in the canopy), and Wood Zoning (the position of branches and twigs in the canopy). Bark Texture and Bark Color were concluded to have negligible impact on shading and therefore were disregarded. Significant differences and associated impacts on the reflectivity, absorptivity, and transmissivity of a tree canopy were identified from the illustrations with regard to Wood Grain. In terms of Wood Density, significant differences in the dimensions of upper trunk parts, branches, and twigs were found in the sample illustrations, with finer branches and twigs resulting in a finer overall density of wood and vice-versa. These were also concluded to have an impact on shading. Further variations were found in the distribution of branches and twigs, with some trees having an even zoning outside of the crown while others demonstrated irregular zonings of branches and twigs, leading to clumping of foliage. As such Wood Zoning was identified as a third critical factor for reflectivity, absorptivity, and transmissivity of solar radiation.

2.1.3 The Elaboration and Selection of Sub-Traits Specific to Foliage

Characteristics of Foliage emerging from analysis of the illustrations included Leaf Size, Leaf Shape and Leaf Color. Other identified relevant sub-traits included Foliage Texture, Foliage Luminance, Foliage Hue, and Foliage Chroma. Further analysis and comparison of other leaf attributes from the botanical illustrations was hampered by incompleteness of the illustration sets; not all of the 101 species in *The Architecture of Trees* included a description and illustration of leaf sub-traits, and comparing monochrome pen and ink drawings from *The Architecture of Trees* with the color plates in *Illustrated Trees of Britain & Europe* proved often too limiting for sound conclusions. As such, further elaboration of Foliage sub-traits occurs in Step Two with the discussion and refinement of the descriptive framework.

2.2 Step Two: Discussion and Refinement of the Descriptive Framework

2.2.1 Selection of Tree Growth Stages

The aim of the research is to develop a descriptive framework of architectural characteristics of trees impacting reflection, absorption, and transmission of solar radiation. Trees grow and develop however, which demands that the framework take this into account. The first section of the framework for crown architecture is thus dedicated to a general description of growth attributes using textual descriptions accompanied by drawings of the overall crown form and related trunk and branching structure of the tree in its various growth stages. Which growth stages to elaborate on is firstly dependent on when trees practically offer shade benefits. Growth stages of trees in cities that offer realistic shade benefits include those in the generative period of tree growth[31], i.e. the young, adult, and mature stages. Trees in the post-generative growth period may be considered optimal in terms of shading, but due to the low occurrence of these trees in most urban environments this category was omitted.

A further refinement focused on a particular growth stage within the generative period in the following sub-trait description sections. This decision was made based on the most common growth stage at which urban trees have an impact on cooling, i.e. the average life-span of urban trees. Estimates of the average life expectancies of trees in North American cities are between 19 and 28 years[32], meaning that on average very few trees survive to the mature growth stage. On this basis the focus growth stage for the descriptive framework was determined as the adult phase, which for most trees corresponds to ages between 19 and 28 years. For reference purposes, general descriptions of mature and young tree growth stages were also included in first section on growth characteristics.

2.2.2 Crown Sub-Traits and C-TAT Classes

Further review of the sub-trait Crown Proportion subsequent to the analysis of botanic illustrations involving studies of 75 specimen trees in dedicated field laboratories revealed that variations in width-to-height ratios of the crown was the most critical factor in tree cooling performances. This criticality arises from differences in the proportional area of crown (surface) impacting the degree of reflectivity, absorptivity, and transmissivity of solar radiation. Given that the sun in the warmest hours of the day in summer periods in temperate cities is positioned in the upper hemisphere of the sky (i.e. a high solar incidence angle), tall, thin tree crowns will have effectively less surface area to reflect intercept or transmit radiation than low, wide crowns. In other words, the total surface area for reflection and interception of solar radiation critically varies with the width-to-height ratio of the crown, relative to the solar incidence angle. It was noted at the same time that the solar incidence angle is highly dynamic, varying throughout the day and at different times of the year. The impact of these variables in other climate zones exceeds the scope of this paper and should be further examined in a follow-up study. For the purposes of the descriptive framework, the aforementioned conclusion was considered sound enough to establish Crown Proportion as the primary sub-trait. The section on Crown Proportion included a written description accompanied by an elevation projection drawing of the adult tree of the species. Average crown radius and average crown heights of the adult specimens were also included.

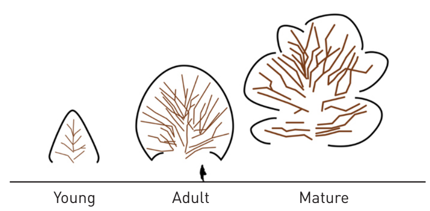
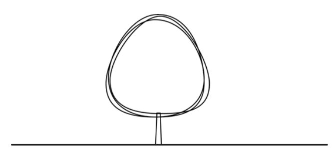
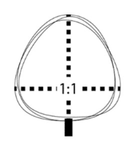
In the definitive framework this proportional key is preceded by a description of growth stages of a tree species accompanied by elevation drawings depicting crown outlines and related branch configurations. The descriptive framework also includes a section on Crown Shape with a written description accompanied by drawings of the crown shape of the adult specimen tree (Table 2). The total number of crown shapes from the sample was established as eight, but more crown shapes may emerge from analysis of additional illustrations.

2.2.3 Wood Sub-Traits and C-TAT Classes

Observations of specimen trees in dedicated field laboratories confirmed that cooling performances from Wood sub-traits, i.e. Wood Grain, Wood Density, and Wood Zoning, can be expected through the related foliage characteristics of reflection and interception of radiation. Variations in these sub-traits allude to fundamental mechanisms that determine the woody architecture of a tree as elaborated in morphogenetic studies such as by Francis Halle, Roelof Oldeman, and Phillip Tomlinson[22]. Based on these studies, the revised descriptive framework section on Wood sub-traits includes descriptions of morphological patterns of trunk, branches, and twigs in text and elevation drawings. These are elaborated for the adult tree but also augmented by descriptions and drawings for young and mature trees.

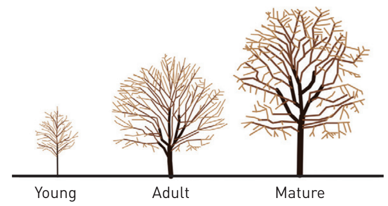
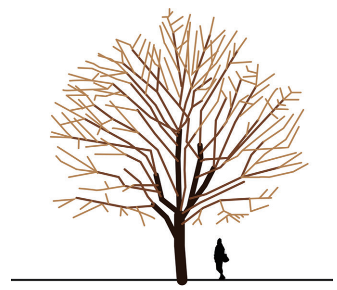
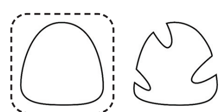
The resulting key for the typology categorization was thereafter established firstly from the observed interrelationship of Wood Grain and Wood Density, which translates into three classes:

Table 2: Crown descriptions and classification key for *Prunus avium* (example)

	Description	**Illustration**
Growth Attributes	· Fast-growing, relatively short-lived (100 ~ 150 years), deciduous tree · Young *Prunus avium* (5 ~ 30 years) have erect-pyramidal “coniferous” crowns which turn into an ellipsoid form as they become adult · The adult phase of *Prunus avium* is between 30 to 60 years with a height of 15 ~ 25 m · Reiteration in mature stage can lead to clumping of the upper crown and fragmentation of the lower crown; mature specimens have columnar crowns and can reach a height of 30 meters in the Cfb climate zone	
Crown Shape	Adult *Prunus avium* typically have an ellipsoid canopy but some specimens will develop a paraboloid or conical canopy depending on growing conditions	
	Classification	**Illustration**
Crown Proportion	Crowns of free-standing adult specimens have a width-to-height ratio of 1:1	

1) Coarse Grain–Low Density, 2) Average Grain–Medium Density, and 3) Fine Grain–High Density. Wood Zoning is an additional and relatively independent sub-trait which determines the overall distribution of leaves of the crown affecting reflection, interception, and transmission of radiation through clumping of foliage. An even and concentric zoning of branches and twigs will result in a more continuous foliage structure with even performance of reflection and interception of radiation, while less even, more random branching will lead to a mix of concentrated and less concentrated patches of foliage. Trees in the sample illustrations were found to be able to be classed into either Even or Uneven Wood Zoning classes (Table 3). In the definitive descriptive framework this pair of

Table 3: Wood descriptions and classification key for *Prunus avium* (example)

Description		Illustration
Growth Attributes	· The uniform rhythmic growth of branches and twigs give young *Prunus avium* prominent cone-shaped crowns · Mature trees reiterate the branching complex of young trees in the top half of the crown, which is a sequential process and gives rise to a more complex crown with a denser wood structure, while lower branches and twigs continue to die off and disappear, resulting in a more open underside of the crown	
Trunk	· The main stem of an adult *Prunus avium* has an orthotropic axis with monopodial, indeterminate growth · The trunk grows rhythmically (in seasonal phases) and develops a slender, tapering bole · A dominant apical meristem persists well into the adult phase, but as the tree reaches maturity the trunk splits into two or more meristems in the top third of the crown	
Branches	· Main branches of adult trees are predominantly plagiotropic, slanting slightly up or down · Branching is spiral, with intervals on the vertical axis of 0.2 ~ 2 m, and typically extend out to half the height of the crown · All branches have determinate growth, with around a third dying off between the young and adult phases · Die-off occurs mainly in the lower half of the crown, resulting in open patches and less densely vegetated axes	
Twigs	· Twigs grow both orthotropically and plagiotropically, and typically also in downward direction · Twigs' growth is medium-term, determinate and rhythmic, and twig density increases near the top half of the crown where less die-off occurs · Typical wild *Prunus avium* are smaller annual twig complexes (brachyblasts), and these very short axes produce a single cluster of leaves every year with no particular growth direction and short-term, determinate growth (5 ~ 7 years)	
Classification		**Illustration**
Wood Grain and Wood Density	Fine Grain–High Density for adult specimens	
Wood Zoning	The organization of wood in the crown is Even	

keys is preceded by a description of growth stages of a tree species accompanied by elevation drawings depicting its typical trunk, branch, and twig morphology.

2.2.4 Foliage Sub-Traits and C-TAT Classes

In reviewing and elaborating on findings on Foliage from the illustration sets and observations of specimen trees in field laboratories, it was determined that the sub-traits Foliage Hue (basic color) and Foliage Chroma (color intensity) have limited impact on cooling and thus represented characteristics extraneous to the framework. Foliage Texture and Foliage Luminance, however, were concluded to be critical for shading and thus identified as key classification categories for the framework. From field observations, it was established that the contributing characteristics for Foliage Texture and Foliage Luminance are dependent on leaf attributes and their arrangement. The descriptive framework thus elaborated on leaf characteristics identified in the illustrations (Leaf Size, Leaf Shape, and Leaf Color) augmented by characteristics emerging from studies in field laboratories as well as descriptions from benchmark dendrological reference manuals by Gert Krüssmann[33], Jan de Koning et al.[34], and Jesus San-Miguel-Ayanz, et al.[35]. This process resulted in additional relevant leaf sub-traits including Leaf Thickness, Leaf Texture, Leaf Orientation, and Leaf Arrangement. Photographic studies of Foliage sub-traits from controlled field-plot arboreta of selected tree species and cultivars form the basis of two description sections of text and photographs on Leaf Attributes (including Leaf Size, Shape, Color, Thickness, Texture, and Orientation) and Leaf Arrangement. A section on seasonal performances of Foliage and Foliage Phenology, was also included (Table 4).

The resulting classification for use in the typology categorization builds on these descriptions by synthesizing leaf characteristics

Table 4: Foliage descriptions and classification key for *Prunus avium* (example)

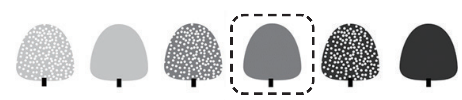
Description		Illustration
Leaf Attributes	· Size: 6 ~ 15 cm in length, with an average area of 50 cm^2 · Shape: simple, ovate to obovate, with serrated margins and a pronounced pointed apex · Color: dark-green topside, light-green underside · Texture: smooth topside, hairy underside; slightly leathery to touch · Thickness: relatively thin · Orientation: semi-vertical to vertical	
Leaf Arrangement	· Smaller annual twig complexes (brachyblasts) are typical for *Prunus avium* · Leaves are pendulous, spaced alternately (distichous) along metamers, with clusters of leaves at the proximal end of the internode · At the metamer scale both the leaf and the leaf unit are stratified in a pronounced horizontal fashion	
Foliage Phenology	· *Prunus aviumis* a deciduous tree with an average in-leaf season in the Cfb climate zone of 200 days · *Prunus avium* attains full leaf cover around mid-May, begins autumn coloration in mid-October and fully sheds its foliage by mid-December	
Classification		**Illustration**
Foliage Texture	Fine	
Foliage Luminance	Medium	

Table 5: Descriptive framework

Description		Classification	
Crown	Growth Attributes	Crown Proportion	• < 1:1 • 1:1 • 1:1.5 • 1:2 • > 1:2.5
	Crown Shape		
Wood	Growth Attributes	Wood Grain and Wood Density	• Coarse Grain–Low Density • Average Grain–Medium Density • Fine Grain–High Density
	Trunk Morphology		
	Branch Morphology		
	Twig Morphology	Wood Zoning	• Even • Uneven
Foliage	Leaf Attributes	Foliage Texture and Foliage Luminance	• Coarse–Light • Fine–Light • Coarse–Medium • Fine–Medium • Coarse–Dark • Fine–Dark
	Leaf Arrangement		
	Foliage Phenology		

into two categories: Foliage Texture and Foliage Luminance. Variations in Foliage Texture appeared in all tree illustrations, but significant differences in field studies of specimen trees leading to a large number of categories were not noted. On the basis of the sample sets and through field studies of specimen trees, two primary texture classes were established: Fine Foliage Texture and Coarse Foliage Texture. It should be noted that Foliage Texture is an alternative to existing canopy indices such as leaf area index (LAI)③[36]. Differences in Foliage Luminance identified in the illustration sources were further validated in the field. Using the lightness value scale from colorimetry, all trees in the field studies were able to be assigned one of three luminance values: 2, 5 or 8, corresponding to luminance classes of Light, Medium or Dark. Using combinations of these two categories, trees can be described and classified into one of six categories for use in the C-TAT typology: 1) Coarse–Light, 2) Fine–Light, 3) Coarse–Medium, 4) Fine–Medium, 5) Coarse–Dark, and 6) Fine–Dark.

3 Conclusions

As the elementary unit of urban forests, trees temper thermal extremes but metrics on the shade performance of different species is currently limited, due to the challenges of measuring the large number of species and cultivars and in knowing exactly what to measure and how. These challenges can be aided by the development of a structured overview of the physical characteristics of trees that impact solar radiation reflectivity, absorptivity, and transmissivity. The development of the descriptive framework is based on the concept of tree architecture, which presents itself as an appropriate term for use on physical characteristics of trees that impact solar radiation reflectivity, absorptivity, and transmissivity and for the development of C-TAT.

The framework describes various architectural sub-traits within the overall categories of Crown, Wood, and Foliage, and offers a structured and comprehensive overview of tree architecture impacting reflectivity, absorptivity, and transmissivity of solar radiation (Table 5). Sub-traits within these overall categories included in the descriptive part of the framework include: 1) Crown Shape, 2) Trunk Morphology, 3) Branch Morphology, 4) Twig Morphology, 5) Leaf Attributes, and 6) Leaf Arrangement.

③ LAI is the total one-sided area of leaf tissue per horizontal ground unit area (source: Ref. [36]).

Given the average maximum age of trees in urban areas (and their corresponding optimum effectiveness for shading urban microclimates) the focused growth stage for elaboration of these sub-traits is the adult phase, but general descriptions of young and mature tree growth stages are also included in the descriptive framework for reference purposes. The various sub-traits are elaborated using text, elevation drawings, photographs, and diagrams.

Classes leading out from these sub-traits for use as a key in C-TAT include five Crown Proportion classes (< 1:1, 1:1, 1:1.5, 1:2, > 1:2.5), three Wood Grain and Density classes (Coarse Grain–Low Density, Average Grain–Medium Density, and Fine Grain–High Density), two Wood Zoning classes (Even and Uneven), and six classes combining Foliage Texture and Foliage Luminance (Coarse–Light, Fine–Light, Coarse–Medium, Fine–Medium, Coarse–Dark, and Fine–Dark). These can be used to organize the many species and cultivars occurring in Cfb climate zone to a lesser number of architectural types for more rapid evaluation and cooling performance calculations. It may also be valuable in assisting tree managers to propose more accurate thermal performance standards for trees in urban projects. The elaboration from an urban microclimate perspective complements existing elaborations and approaches in the field of tree architecture.

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https://doi.org/10.15302/J-LAF-1-020084 收稿日期 | 2022-11-26 修改日期 | 2023-07-21 录用日期 | 2023-09-10 中图分类号 | TU986 文献标识码 | A

提供荫凉的树木
——针对缓和城市局地气候的树木形态类型学描述框架

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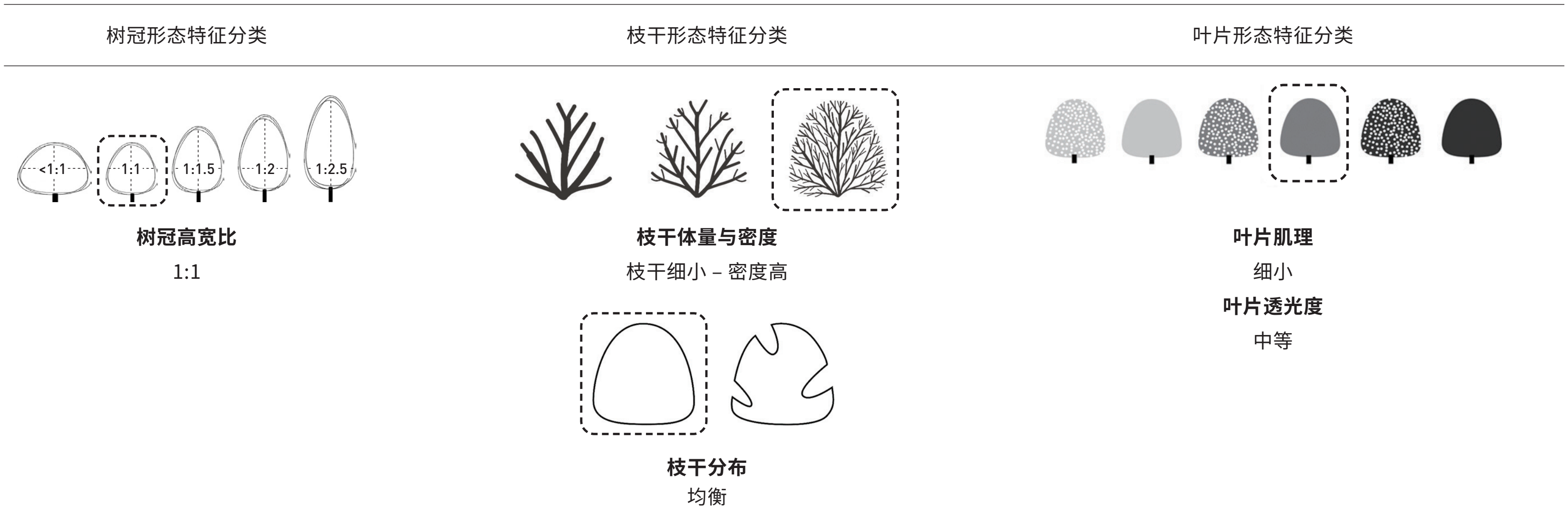
图文摘要

本文提出的描述性框架为“可提供阴凉的树木形态类型学”特征分类提供了参考依据

以欧洲甜樱桃（*Prunus avium*）为例



摘要

作为城市森林的基本单元，树木可通过遮荫和蒸腾，以及改变空气流动等途径来调节城市局地气候中的极端高温。然而，目前用来衡量不同树种遮荫效果的指标还很有限，因此需要开发一种新的方法来填补。本文提出了一种通过对影响太阳辐射反射率、吸收率和透射率等树木物理特性进行结构化描述来筛选树种的方法。这一描述性框架基于“树木结构”概念——树木结构已发展成为植物研究领域中一个专门研究植物的外观、形态和发育过程的方向。该框架包含了树冠、枝干和树叶三大总体特征中的多个子形态特征，可用于探究“可提供荫凉的树木形态类型学”（Cool Tree Architecture Typology，C-TAT），并将具有共同物理特征的树种进行分类。通过树木的野外对照实验观察，进一步细化了子形态特征，形成了新的描述指标，成为了C-TAT分类的关键。C-TAT适用于大西洋气候带等地区的城市中的树种形态类型划分，可对现有树木进行更快速的评估和降温绩效计算，并有助于树木管理者对城市开发项目中的树木制定更准确的热性能标准。本文也从城市局地气候的角度丰富了树木结构的研究内涵与方法。

文章亮点

- 提出了一个反映影响太阳辐射反射率、吸收率和透射率的树木形态特征的描述性框架
- 有助于降温的关键性树木形态特征指标包括树冠高宽比、枝干体量、枝干密度、枝干分布、叶片肌理和叶片透光度
- 该描述性框架可用于探究“可提供荫凉的树木形态类型学”，并将具有共同物理特征的树种进行分类，可用于制定与改善局地热环境气候有关的城市树木指标和标准

关键词

树木结构；城市热岛；气候适应；城市局地气候调节；可提供荫凉的树木形态类型学

编辑 田乐，高雨婷