Journal of Environmental Quality
SPECIAL SECTION
THE URBAN FOREST AND ECOSYSTEM SERVICES

Branch Area Index of Solitary Trees: Understanding Its Significance in Regulating Ecosystem Services

J. Deak Sjöman,* A. Hirons, and H. Sjöman

Abstract

The chief aim of this study was to investigate how different species of solitary trees in temperate urban areas vary in their branch structure during winter by assessing branch area indices (BAIs). The BAI data showed significant differences ($P < 0.0001$) between species and genotypes. The lowest mean BAI in the dataset was for *Gingko biloba* L., which had a BAI of 0.27. *Pinus strobus* L. 'Fastigiata' represented the largest mean BAI of 2.09. The results from the BAI analysis further indicate that within the same species group differences occur between genotypes. For example, the five genotypes of *Acer platanoides* L. range from a mean BAI of 1.77 for *A. platanoides* 'Globosum' to a mean BAI of 0.50 for *A. platanoides* 'Fassen Black'. A further aim was to apply the compiled BAI data in the computational modeling program of ENVI-met 3.1, which simulates the surface–air interaction and microclimates in complex urban settings. The simulations focused on mean radiant temperature and wind speed. Results illustrate how wind speed on the leeward side of the trees gradually decrease with an increasing BAI. With an increasing BAI, the Tmrt decreases to the leeward of the row of trees. The results are further discussed in the perspective of sustainable urban development (i.e., where, why, and how the species studied could be integrated in the urban fabric). This is of particular interest for the design of urban green space in densely built-up urban environments where space may be restricted.

Core Ideas

- Branch density and architectural make up of solitaire trees differ in winter.
- Branch area indices vary significantly between species and genotypes of trees.
- Different branch area indices will influence mean radiant temperature and wind speed in a complex urban setting.
- The results are discussed with regards to the design of urban green space.

Recent years have seen a number of research studies on how the urban forest contributes to a wide range of ecosystem services. This includes the mitigation and adaptation to climate change by moderating the adverse effects of the urban heat island effect and urban runoff (Xiao and McPherson, 2002; Gill et al., 2007; Brown et al., 2015). Additional studies have shown how trees can help reduce energy use in buildings and increase thermal comfort during hot summer days (Akbari et al., 2001; Nikoofard et al., 2011; Shashua-Bar et al., 2011; Sawka et al., 2013). In temperate climates, where the use of broadleaved trees in the urban landscape dominates (Sjöman et al., 2012; Cowett and Bassuk, 2014), the design for shade in summer and adequate solar transmission for passive heating regulation in winter is essential (Sawka et al., 2013). Although some species have a very dense make-up of branches in winter, others present a more sparse composition in their branch architecture. This in turn affects the extent of solar transmissivity through the canopy and magnitude of wind flow (Heisler, 1990; Cantón et al., 1994; Kontogianni et al., 2011; Konarska et al., 2013).

However, in most studies concerned with urban tree cover in the Northern Hemisphere, potential ecosystem services are evaluated in summer when trees are in full leaf. It has been concluded that the urban tree canopy provides most beneficial effects to the community and building energy use during warmer periods in cooling the urban landscape and moderating high temperatures (Dimoudi and Nikolopoulou, 2003; Fryd et al., 2011). Even if winter conditions and deciduous trees with no leaf cover are included, little information is provided regarding species or important tree attributes. In computational modeling for microclimates in complex urban settings, the distinction between summer or winter attributes in the tree input data is also lacking (e.g., ENVI-met and RayMan) (Bruse, 2009; Matzarakis et al., 2007). Although a few research studies exist on solar transmissivity and trees with no leaf cover, only four or five species have been included based on the most commonly used species for solitary urban planting (Cantón et al., 1994; Konarska et al., 2013).

The building industry presents a repertoire of technical information concerning different building materials, which in turn make up an integral part of the evaluation programs of, for

J. Environ. Qual.
doi:10.2134/jeq2015.02.0069
Received 2 Feb. 2015.
Accepted 28 May 2015.
*Corresponding author (johanna.deak.sjoman@slu.se).

J.D. Sjöman and H. Sjöman, Dep. of Landscape Architecture, Planning and Management, Swedish Univ. of Agricultural Sciences, Alnarp 230 53 Sweden; A. Hirons, Myerscough College, Bilsbarrow, Preston, Lancashire, PR3 0RY, UK.
Assigned to Associate Editor Gregory McPherson.

Abbreviations: BAD, branch area density; BAI, branch area index; LAD, leaf area density; PET, physiologically equivalent temperature; Tmrt, mean radiant temperature.

example, LEED (USGBC, 2014) and the BRE Environmental Assessment Method (BREEAM, 2014). It could be argued that a similar approach is called for regarding greenspace design. In temperate parts of the world, this includes a better understanding in how greenspace design can be integrated as eco-technical components and used in sustainable planning and design during those parts of the year when deciduous plants are without foliage.

Furthermore, with the current and predicted increases in disease and pest outbreaks in urban forests, the diversity of species and genera needs increasing throughout the urban landscape (Tubby and Webber, 2010). Cities relying predominantly on few species or genera may suffer severe losses to the overall urban tree canopy when hit by pests and disease (Tubby and Webber, 2010). Furthermore, some of the most commonly used species in Scandinavia's urban paved environments originate ecologically from moist woodland habitats (Sjöman et al., 2012). With increasing temperatures due to climate change and intensified water stress, introducing species with ecological strategies capable of persisting through more protracted periods of stress during warm and dry periods may become critical (Sjöman et al., 2012). This perspective helps support why a wider range of different species needs to be included in studies on tree attributes for climate modeling.

The chief aim of this study was to investigate how different species of solitary trees vary in their winter branch area index (BAI). An additional aim was to apply the compiled BAI data in the computational modeling program of ENVI-met 3.1, which simulates the surface–air interaction and microclimates in complex urban settings. The simulations focused on mean radiant temperature (Tmrt) and wind speed. The calculated Tmrt was then applied to the RayMan software, which, together with the additional input of air temperatures and humidity, was used to calculate physiologically equivalent temperature (PET) (Matzarakis et al., 2010). These data were then used to inform a discussion on how contrasting tree species may influence thermal comfort, the significance of tree selection on regulating ecosystem services (of Tmrt and wind speed modification), and climate responsive design implications for urban greenspace in winter.

Materials and Methods

Branch Area Index Data

The BAI data were collected at two sites: (i) the Urban Tree Arboretum at Hørsholm, Denmark (55°52′49 N 12°30′29 E) and (ii) Cornell Plantations at Cornell University in Ithaca, NY (42°27′0 N, 76°28′19 W). At the Urban Tree Arboretum, 72 broadleaved tree species/genotypes were analyzed, whereas indices of one tree species (*Pinus strobus* L. 'Fastigiata') were collected at Cornell Plantations (Table 1). All trees in the study were solitary grown and nonpruned. Although the Urban Tree Arboretum presents trees subjected to different pruning techniques (Bühler and Kristoffersen, 2009), nonpruned trees were chosen to provide an authentic example of different species' crown architectural characteristics (the intervention from pruning can cause significant alteration to inherent tree characteristics). Only the initial lower branches were cut to allow for maintenance access (i.e., 1.5–2 m clearance height for nonfastigiate species).

According to Myneni et al. (1997), LAI represents the maximal projected leaf area per unit ground surface area and includes leaves, branches, and trunk. In seasons when leaf cover for deciduous trees is absent, the same projection will include branches and trunk only and is consequently referred to as BAI (Kumakura et al., 2011). The BAI data for each tree were collected by using a Digital Plant Canopy Imager (CI-110) (CID Bio-Science, 2013), which captures wide-angle canopy images with a subsequent estimate of BAI. The CI-110 involves a fish-eye camera positioned at the end of a 0.8-m rod that is connected to a digital touch screen where hemispheric images of digital projections beneath the tree canopy are processed and adjusted. The BAI values were based on a one-sided projection of the branches within the crown projection area.

All trees at The Urban Tree Arboretum at Hørsholm and at the plantation at Cornell University were planted as solitary individuals, and no additional objects of tree branches of adjacent trees, people, cars, etc. were visible in the captured images. Previous experience in using the CI-100 equipment indicated high sensitivity to shifting light conditions, and as such the scans for this study were taken on days with full cloud cover to ensure a diffuse light source. Before each scan, light conditions were established using an exposure meter to provide consequent index values.

Four digital scans of each tree species were taken at three separate field visits during winter in 2013–2014. Each tree was thus scanned four times (south, west, north, and east) 0.5 m away from its trunk and 0.5 m above ground level at each field visit. Scans were analyzed using the image processing tool provided with the Digital Plant Canopy Imager, and regions outside the crown projection (i.e., with no outer ring of the frame photo area) were excluded from analysis. Four points (north, south, east, and west) were assessed on each tree, and these values were used to calculate the mean species value. The standard error presented, therefore, represents the variation found within the crown of a single individual.

Similar to Peper and McPherson (2003), the threshold adjustments proposed some subjectivity because BAI values could easily be manipulated by different settings of brightness, γ, or threshold values. To overcome this, each scan was processed consistently with contrast values set to 100%, brightness to 45%, γ at 50%, and an Otsu method threshold value ranging from 69.92 to 72.66%. To keep within the scope of accuracy, all the mean BAI values were subsequently compared with branch area indices mentioned in previously published literature (e.g., Breuer et al. [2003] and Wang et al. [2008]).

Microclimate Simulations

The ENVI-met 3.1 model is made up by a relatively simple and one-dimensional soil model, a vegetation model, and a radiative transfer model (Bruse and Fleer, 1998). Jointly these compose a Computational Fluid Dynamics model with a special focus on the surface–plant–air interaction. In ENVI-met 3.1 the soil and ground surface materials have properties such as thermal capacity and thermal conductivity, which means that the heat storage of the ground is taken into account (Bruse, 2009). On the other hand, buildings (i.e., walls and roofs) have no thermal mass, which means heat storage is not considered, and consequently the surface temperature of a facade exposed to solar radiation is likely to be overestimated and may indicate a falsely high Tmrt. In this study, the albedo for the walls was given a relatively high value (0.7), and as such the increase in surface temperature

Table 1. Inventory of all species included for the branch area index calculations.

Species	Planted	DBH†	Tree height‡	Canopy height§	Crown diameter
		cm	m		
Acer campestre	2001	18.79	8.4	6.0	6.95
Acer campestre 'Elsrijk'	2001	11.78	7.8	5.8	3.375
Acer negundo	2001	15.92	8.0	6.2	5.65
Acer platanoides	2001	15.61	7.3	5.0	6.125
Acer platanoides 'Columnare'	2001	21.34	11.5	9.5	6.96
Acer platanoides 'Emerald Queen'	2001	17.20	11.0	8.9	6.025
Acer platanoides 'Fassen Black'	2001	16.79	11.0	8.9	5.725
Acer platanoides 'Globosum'	2001	13.69	5.0	2.7	4.525
Acer pseudoplatanus	2001	15.92	8.0	6.2	5.285
Acer pseudoplatanus 'Negenia'	2001	10.19	6.7	4.7	3.71
Acer pseudoplatanus 'Rotterdam'	2001	17.83	13.0	10.5	4.71
Acer rubrum	2001	11.78	11.5	9.3	4.37
Acer saccharinum	2001	26.11	15.0	12.8	6.42
Aesculus carnea 'Briotii'	2001	14.65	7.3	5.5	5.345
Aesculus hippocastastanum	2001	21.97	8.0	6.1	5.29
Aesculus hippocastastanum 'Baumannii'	2001	19.11	8.0	5.8	4.875
Ailanthus altissima	2004	12.74	6.5	4.1	3.815
Alnus cordata	2001	20.06	15.5	11.5	5.14
Alnus glutinosa	2001	11.46	10.0	7.0	3.74
Alnus × *spaethii*	2001	12.12	10.2	8.3	5.10
Carpinus betulus 'Fastigiata'	2001	15.61	9.0	7.9	4.675
Carpinus betulus	2001	13.69	8.0	6.7	5.21
Castanea sativa	2001	22.93	8.3	6.4	6.04
Corylus colurna	2001	12.42	8.1	6.0	2.745
Fagus sylvatica	2001	10.83	7.8	6.3	4.65
Fraxinus americana 'Zundert'	2001	14.33	9.0	6.8	4.365
Fraxinus angustifolia 'Raywood'	2001	19.75	14.5	11.6	5.57
Fraxinus excelsior 'Robusta'	2001	19.43	10.0	8.0	5.02
Fraxinus excelsior 'Westhof´s Glorie'	2001	16.24	8.8	6.9	4.515
Fraxinus ornus	2001	15.24	8.4	6.3	4.4
Ginkgo biloba	2001	7.01	6.8	4.5	0.83
Gleditsia triacanthos	2001	11.15	5.8	2.1	3.695
Liriodendron tulipifera	2001	16.24	11.0	8.1	4.39
Metasequoia glyptostroboides	2001	11.15	8.2	7.1	2.275
Pinus strobus 'Fastigiata'	1996	12.20	9.1	6.2	2.8
Platanus acerifolia	2001	17.20	11.0	9.0	5.545
Populus alba 'Nivea'	2001	30.57	15.0	12.5	10.26
Populus canescens 'De Moffart'	2001	44.27	17.0	15.0	14.435
Populus trichocarpa 'OP42'	2001	36.31	20.0	18.5	8.43
Populus trichocarpa 'Poca'	2001	36.94	20.0	17.8	7.67
Prunus avium	2001	20.38	9.5	7.3	6.78
Pyrus caucasica	2001	13.38	8.2	6.0	4.625
Pyrus communis 'Beech Hill'	2001	19.11	10.0	8.1	7.96
Quercus cerris	2001	22.93	14.0	11.9	6.26
Quercus robur 'Fastigiata'	2001	16.24	9.1	7.9	1.72
Quercus frainetto	2001	17.20	9.5	7.5	3.49
Quercus palustris	2001	16.88	9.3	7.2	6.9
Quercus rubra	2001	20.38	9.0	7.7	5.64
Quercus robur	2001	19.11	8.8	6.8	6.31
Quercus petraea	2001	17.52	9.3	7.4	5.14
Robinia pseudoacacia	2001	23.57	11.3	9.1	7.55
Robinia pseudoacacia 'Bessoniana'	2001	20.70	10.7	8.6	7.09
Robinia pseudoacacia 'Nyirsegi'	2001	23.57	13.0	10.7	7.56
Robinia pseudoacacia 'Umbraculifera'	2001	13.06	8.1	5.8	3.60
Salix alba	2001	28.98	16.0	13.9	6.08

Table 1. Continued.

Species	Planted	DBH†	Tree height‡	Canopy height§	Crown diameter
		cm	m		
Salix alba 'Liempde'	2001	31.85	18.0	15.8	6.80
Salix alba 'Saba'	2001	33.44	18.0	15.8	6.82
Salix alba 'Sibirica'	2001	23.57	8.1	6.3	6.66
Sophora japonica 'Regent'	2001	20.38	8.3	6.3	7.13
Sophora japonica	2001	19.75	6.7	4.7	6.12
Tilia cordata	2001	19.11	7.3	5.1	6.27
Tilia cordata 'Erecta'	2001	20.70	8.0	6.0	5.37
Tilia cordata 'Greenspire'	2001	17.83	8.9	6.9	5.49
Tilia cordata 'Rancho'	2001	15.29	8.0	6.1	4.67
Tilia euchlora	2001	15.61	7.8	5.8	5.29
Tilia euchlora 'Frigg'	2001	16.56	8.3	6.6	4.81
Tilia platyphyllos	2001	21.34	9.1	7.4	6.63
Tilia platyphyllos 'Rubra'	2001	21.66	8.2	6.2	6.69
Tilia platyphyllos 'Örebro'	2001	18.15	10	8.0	5.15
Tilia platyphyllos 'Fenris'	2001	12.74	7.1	5.1	3.98
Tilia europaea 'Pallida'	2001	14.97	8.0	6.2	4.09
Tilia hybrid 'Odin'	2001	17.20	8.2	6.9	5

† Trunk diameter at breast height taken at 1.3 m above ground level.

‡ Total height of the tree (from ground level to top of canopy).

§ Includes measurement from the lowest and initial branches to the top of canopy.

will be limited and the Tmrt increase believed to be small (E. Johansson, personal communication, 2015).

The input parameter for vegetation in the ENVI-met model is that of leaf area density (LAD) ($m^2\ m^{-3}$) and consists of 10 LAD values for each plant. The LAD values are in turn retrieved from a leaf area index (LAI). The physiological properties of the plants in ENVI-met characterize parameters such as moisture absorption by roots, stomatal resistance, and albedo of leaves (Bruse, 2009). Apart from acting as physical obstacles to wind and radiation, the plants in ENVI-met 3.1 interact with the surrounding environment by exchanging heat and water vapor (Ali-Toudert, 2005). In this case, branch area density (BAD) layers constituted the vegetation input data. The following equation explains how the BAI can be calculated given the BAD layers:

$$\mathrm{BAI} = \sum_{i-1}^{n} \mathrm{BAD}_i \times \mathrm{d}z$$

The values for each of the 10 BAD layers were based on an ocular estimation from site observation and photographs taken at a vertical angle of each tree during the field study. Because the ENVI-met model calculates LAD values only, the BAD input data resembled LAD data, albeit with very low LAD values. The latent heat transfer that would occur when the trees are in leaf is thus calculated to some extent in the scenarios for this study. However, such latent heat exchange would not take place because the trees for the date simulated would be dormant.

Meteorological input data comprised of information on initial air temperature, humidity, wind speed, wind direction, and cloud cover. A day in January was chosen to represent winter conditions, and each simulation was set to start at 6:00 AM to cover 12 h finishing at 6:00 PM. Based on the geographical location (latitude and longitude) and cloud cover, the ENVI-met model calculates direct and diffuse solar radiation. Wind velocity is calculated with an increasing gradient in height, making winds stronger at 10 m above ground level compared with 4 m above ground level. The relationship between the two wind speeds can be expressed as:

$$\frac{v_4}{v_{10}} = \left(\frac{4\,\mathrm{m}}{10\,\mathrm{m}}\right)^{\propto} \qquad [1]$$

where $v4$ and $v10$ are the wind speeds at 4 and 10 m height, respectively, and the exponent μ can be put to 0.24 for low-rise residential areas (Johansson et al., 2013). An average wind speed of 5.6 m s^{-1} thus yields a wind speed at 4 m height of about 4.5 m s^{-1}. According to Westerberg and Glaumann (1990–1991), areas subjected to wind of this velocity need appropriate wind breaks.

The geographical area for the microclimate simulations was a fictional case study site representative of recent coastal development schemes in southern Sweden (between coordinates 55°34.8′ N, 13°0′ E and 56°14′ N, 12°51′ E) (Fig. 1). The climatic characteristic of the area is a cold temperate climate with maritime tendencies (Köppen, 2014). The long winter period is characterized by low air temperatures (mean air temperature, 0°C), a lack of sunshine, and strong winds (Meteotest, 2010). Situated by the seafront of Öresund (the strait between Sweden and Denmark), the site was subjected to a mean wind speed of 5.6 m s^{-1} at 10 m above sea level (Meteotest, 2010). The dominating wind direction was set to the west/southwest (see wind rose for the city of Malmö in Fig. 2).

The case study area exemplified a semi-enclosed public square with buildings to the north, east, and south. The buildings were four stories in height with a facade albedo of 0.7 and represent typical building types in contemporary construction. All ground-level surface materials were set to asphalt with an albedo of 0.1. No buildings or structures were placed along the west side of the square; the west side of the square was lined with a street and row of trees only (Fig. 3). Based on previous experiments and observations in similar urban contexts by Westerberg and

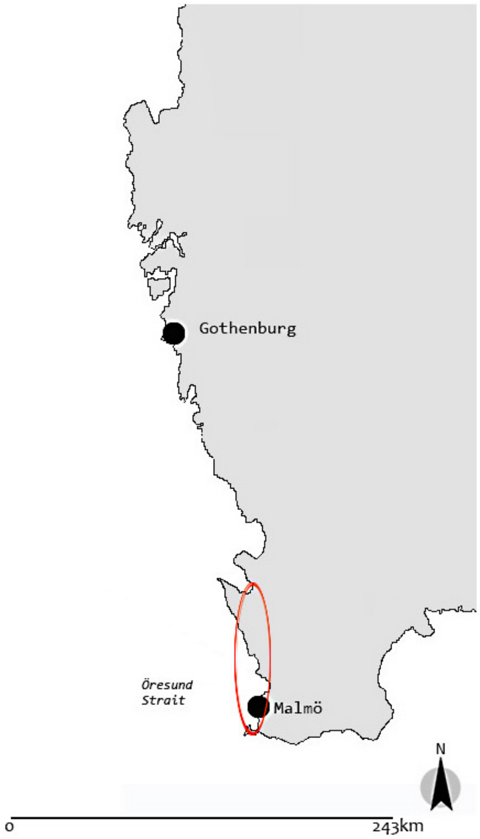

Fig. 1. Map of the coastal area of the Öresund Region in Sweden where the area simulated in the ENVI-met model was located.

Glaumann (1990–1991), Bitog et al. (2012), and Lenzhölzer, (2010), the trees were placed perpendicular to the wind flow in a single-row shelterbelt. The purpose of placing a single row of trees was to examine how different species may influence the lee cavity in the courtyard area depending on their porosity (Oke, 1988; Lenzhölzer, 2010; Santamouris, 2011). The trees were kept to one species only and changed to a different species for each simulation.

Based on the statistical analysis of the BAI calculation, seven simulations were run for *Ginkgo biloba* L., *Acer platanoides* L. 'Emerald Queen', *Gleditsia triacanthos* L., *Quercus cerris* L., *Corylus colurna* L., *Carpinus betulus* L. 'Fastigiata', and *P. strobus* 'Fastigiata'. The species represent a gradual selection of the intermediate and the opposing extremes from the BAI dataset. The *P. strobus* 'Fastigiata' was selected to give an offset from the otherwise broadleaved specimens, and the fastigiate form was chosen to explore its contribution as potential wind break in a built-up urban environment.

The ENVI-met simulations were used to calculate how the different species influenced wind speed at 4 m height and Tmrt at 1.20 m height. The cut at 4 m for assessing wind speed was chosen because some of the trees did not provide a substantial canopy characteristic below this measurement. The height of 1.2 m above ground level was simulated for the Trmt to correspond to the average height of the center of gravity for adults as indicated in Thorsson et al. (2007). The Tmrt was subsequently used to calculate PET using the RayMan model developed by Matzarakis et al. (2010). Physiologically equivalent temperature can be described as the actual temperature that the human body physically senses. The PET calculation incorporate data on Tmrt, air temperature (in this case 0°C), relative humidity (50%), wind speed (which in this case differed depending on scenario), and human attributes such as metabolic rate and clothing (in this case: male, age 35 yr, height 1.75 m, weight 80 kg, clothing factor 0.9, and activity [W] 80).

Results

Branch Area Index Analysis

The BAI data show significant differences ($P < 0.0001$) between species and genotypes analyzed (Fig. 4). The lowest mean BAI in the dataset is *G. biloba*, with a BAI of 0.27, whereas *P. strobus* 'Fastigiata' represents the largest mean BAI (2.09). Notably, the fastigiate trees *C. betulus* 'Fastigiata' and *Quercus robur* L. 'Fastigiata' have mean BAIs of 1.94 and 1.84, respectively, which can be compared with the mean BAI of the species in its nonfastigiate form (1.39 and 0.98, respectively) (Fig. 4).

The results from the BAI analysis also indicate that differences occur between genotypes of the same species. For example, the five genotypes of *A. platanoides* range from a mean BAI of 1.77 for *A. platanoides* 'Globosum' to a mean BAI of 0.50 for *A. platanoides* 'Fassen Black' (Fig. 4).

Microclimate Simulations: Wind Speed

The results from the wind speed simulations indicate how wind speed would taper off further into the courtyard area. Only in the alley between the buildings to the east would wind pick up speed due to increased air pressure and venturi effects. Results also illustrate how wind speed on the leeward side of the trees would gradually decrease in tandem with an increased BAI (Fig. 5a–g). As such, a row of fastigiate trees will provide greater shelter compared with a row of trees where branches are cut at a higher level and where trees comprise of lower BAI values. Comparing *G. biloba* (the lowest of all BAI values) and *P. strobus* 'Fastigiata' (the highest of all BAI values), it is possible to see how wind speed above 3.60 to 4.10 m s^{-1} is prominent in the courtyard area (at the leeward side of the tree row) during the scenario with *G. biloba*.

Microclimate Simulations: Mean Radiant Temperature and Physiologically Equivalent Temperature

In all scenarios simulating Tmrt, Tmrt was the lowest in the center of the courtyard area (i.e., between 3.15 and <1.25°C). This is equivalent to a PET of −6.6°C and approximately −7°C in scenarios with *G. biloba*, *A. platanoides* 'Emerald Queen', *G. triacanthos*, *Q. cerris*, and *C. colurna* (with an air temperature of 0°C, relative humidity of 50%, and wind speed of 3.60–4.10 m s^{-1}). The PET in the center of the courtyard increases to −5.9°C in scenarios with *C. betulus* 'Fastigiata' and *P. strobus* 'Fastigiata' (calculating an air temperature of 0°C, relative humidity of 50%, and wind speed of 3.10 m s^{-1}).

With an increasing BAI, the Tmrt decreases to the leeward of the row of trees (Fig. 6a–g). For example, in the scenario of *G. biloba*, Tmrt values are between 5.05 and 6°C, which is equivalent to a PET of −5.4°C. In the scenario with *P. strobus* 'Fastigiata', Tmrt values are predominantly between 2.20 and 3.15°C to the leeward of the tree row, thus indicating a PET from −6 to 5.9°C.

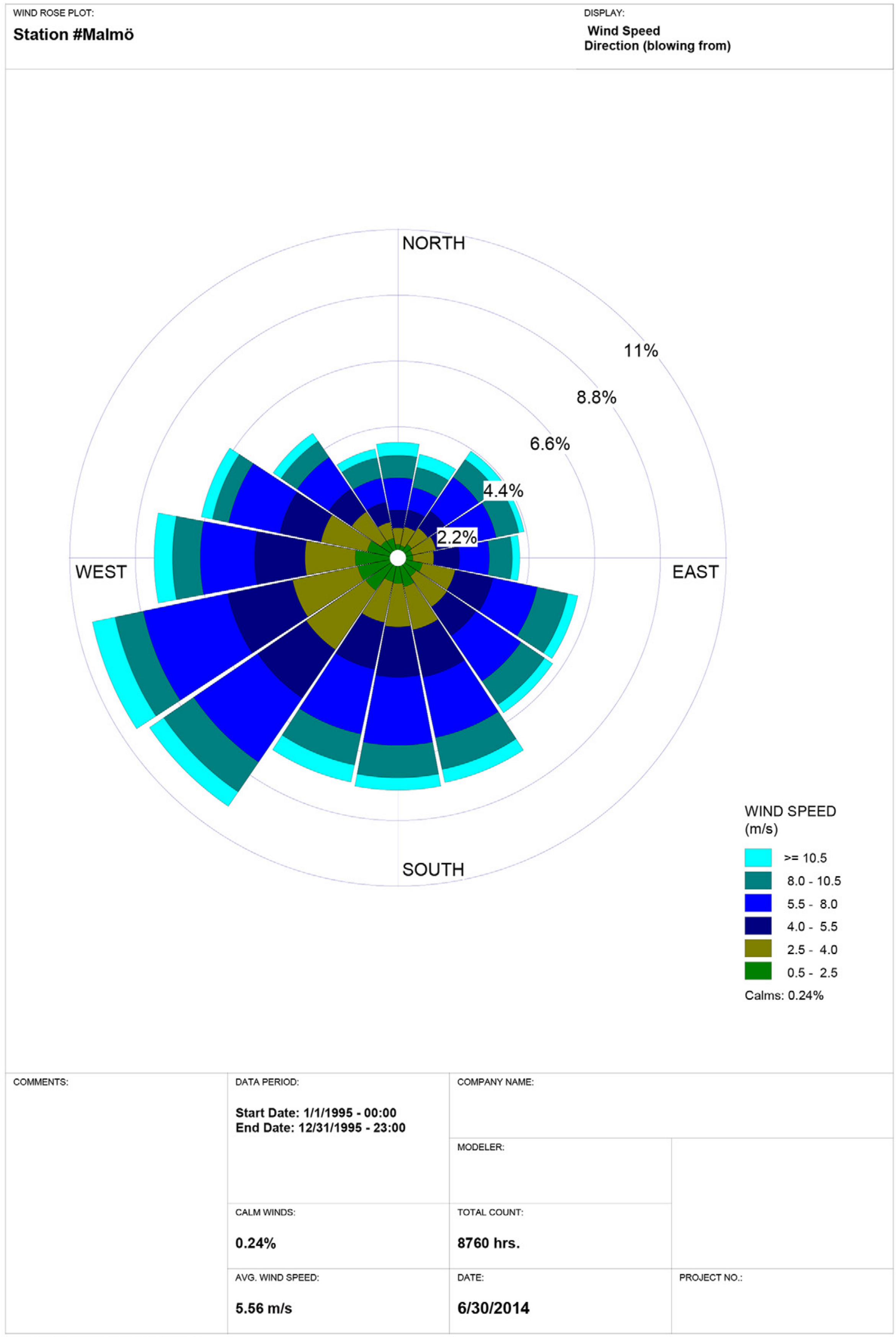

Fig. 2. The wind rose illustrates the most commonly occurring wind directions and wind speeds in the Öresund region, south Sweden, with a predominant wind speed of 5.56 m s^{-1} from the west/southwest.

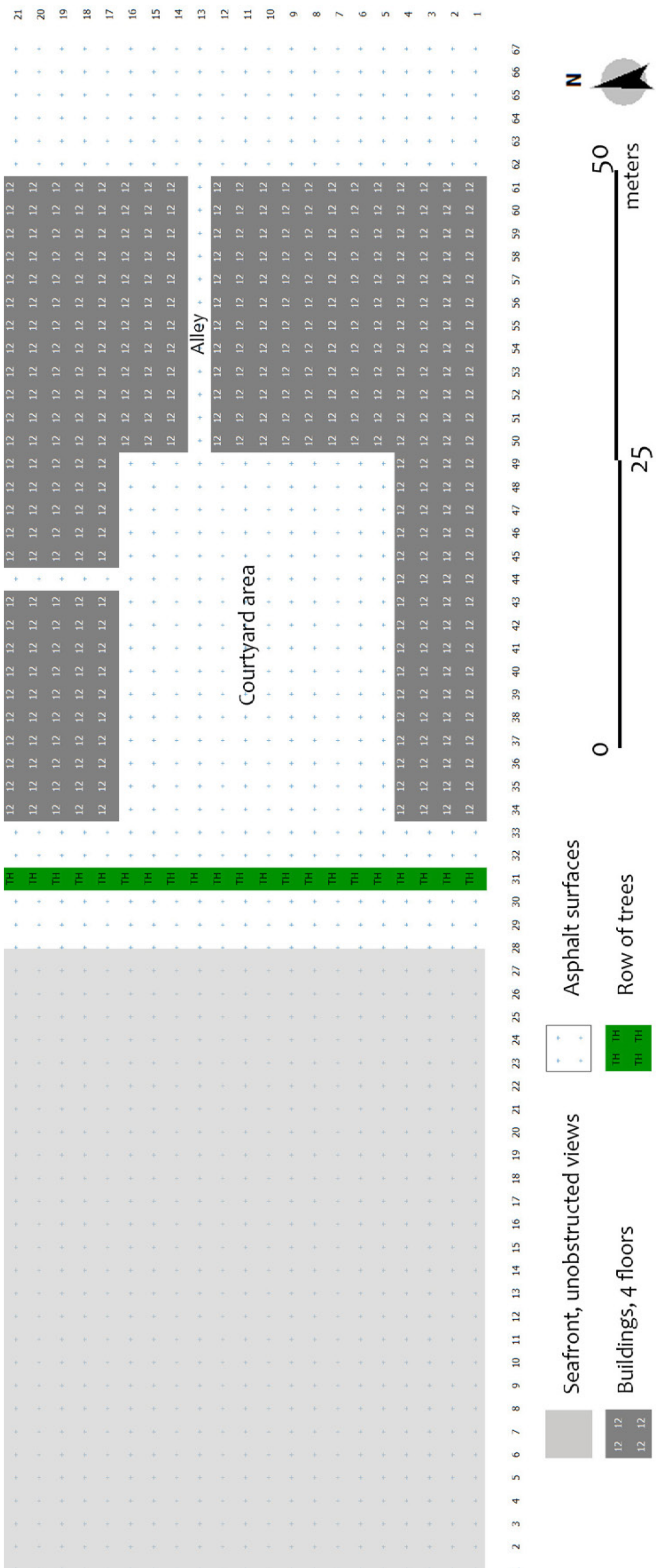

Fig. 3. Conceptual plan of the area simulated in the ENVI-met model. The simulated row of trees is located to the west of a semienclosed courtyard facing unobscured wind flows from the seafront of Öresund.

Discussion

An ideal urban tree in close proximity to buildings in temperate climates would be the one with the lowest transmissivity in summer, when thermal heat stress occurs, but with the highest transmissivity in winter, when sunshine is limited due to fewer sunshine hours and a lower solar azimuth angle. In areas such as public squares or street corners, trees with a denser canopy structure and higher BAI can help decrease wind velocity and wind chill effects if planted strategically so as not to increase shade in direct proximity to seating, playground equipment, or south/southeast building facades.

Although transmissivity data in wintertime from forest stands are available, such data are much less homogeneous compared with a canopy of a single grown tree (e.g., Gay et al., 1971; Liakatas et al., 2002; Hardy et al., 2004). Information concerning transmissivity or BAI of mature solitary grown tree species and genotypes is very limited, especially among untraditionally used species. In Cantón et al. (1994), only four deciduous trees were included [*Platanus acerifolia* (Aiton) Wild, *Morus alba* L., *Fraxinius excelsior* L., and *Melia azedarach* L.]. Also, Konarska et al. (2013) included only five tree species (*Aesculus hippocastanum* L., *Tilia cordata* Mill., *Betula pendula* Roth, *Prunus* spp., and *Pinus nigra* Arnold). However, an increased understanding of how different and more uncommon species can be used in the urban environment is needed to improve outcomes of urban planting schemes and climate-responsive design. An additional motivation is that many traditionally used tree species in the northern hemisphere are facing serious threats from emerging diseases and pests (Sinclair and Lyon, 2005). Increasing the diversity of the urban forest is thus an important step to secure a resilient urban forest. Compared with the repertoire of building materials presented in the evaluation programs of, for example, LEED (USGBC, 2014) and the BRE Environmental Assessment Method (BREEAM, 2014), there is a paucity of information relating to the vital elements of our green infrastructure. By evaluating a wide range of tree species in this study, we have demonstrated the potential importance of species selection to the regulation of Tmrt and wind speed and hope to stimulate further research into the eco-technical design of urban greenspace.

This study presents BAI for 72 deciduous tree species and genotypes and one genotype of pine. It includes mainly broadleaved trees, with the exception of *P. strobus* 'Fastigiata'. With its full leaf cover, the pine has the highest BAI in the dataset. This is comparable to the study presented by Konarska et al. (2013) with a large *P. nigra* growing in Gothenburg. However, dense canopy genotypes, such as upright (fastigiate) deciduous trees (e.g., *C. betulus* 'Fastigiata' and *Q. robur* 'Fastigiata'), had a similar mean BAI to the pine. Such qualities confer an advantage by acting as a wind break, particularly in areas where aboveground space is restricted, but, conversely, high BAI trees may act to the disadvantage of localities where warming and passive heat gain by solar radiation is important in winter. The data also showed highly significant differences between species and cultivars of the same species, demonstrating the importance of tree selection in delivering ecosystem services relating to thermal comfort. Further, regarding

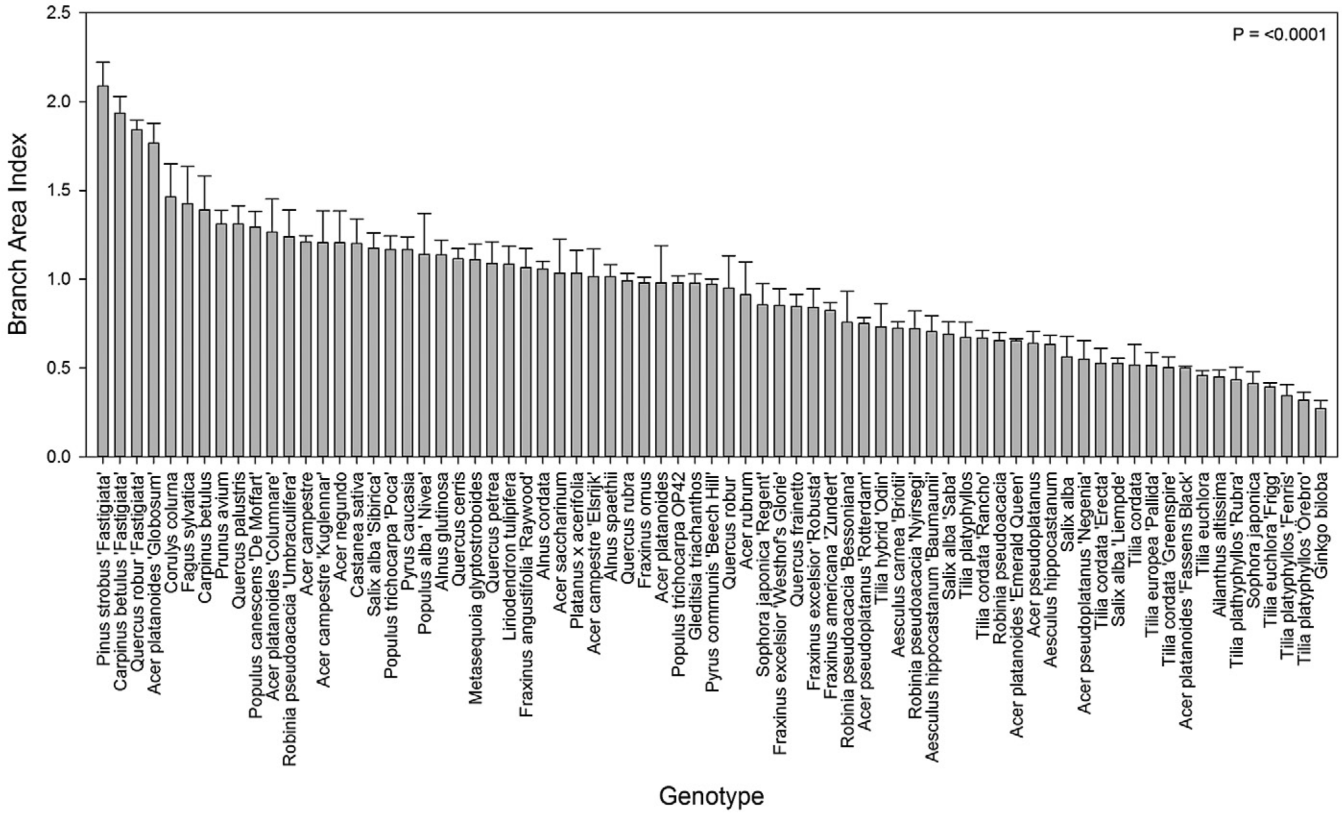

Fig. 4. Branch area index between analyzed species and genotypes. The descriptive statistics of homogeneity is based on Tukey's pairwise comparison (n = 4). P < 0.0001; F = 12.66 at species level. Box-Cox transformation was required to deliver normal residual values.

transmissivity and consequent effects on wind speed and Tmrt, the results highlight the value of designing urban green space with cultivars in mind rather than just selecting between species groups in general.

The results from this study represent individual trees that are young (20–25 yr), and as such their influence on Tmrt and wind speed will change as they mature (height, width, and increased BAI). Mature trees with a higher index value will, for instance, reduce Trmt and wind speed more effectively compared with juvenile trees. Variations of BAI (and LAI in summer) may also occur within the same species group (Nowak, 1996; Breuer et al., 2003). This is particularly true in urban environments where varied growing conditions and pruning may alter area index values. The results from this study need to be put into this context, and landscape professionals involved in tree planning and design must consider the flexibility of how even the solitary and individual tree will influence the microclimate differently throughout its life cycle.

Microclimate conditions influence the use of public places and people's recreational preferences (Lenzhölzer and Koh, 2010). In winter, low Tmrt and wind chill effects further affect microclimate perception. Low solar azimuth angles and limited hours with sunshine require south-facing facades to be unobstructed to gain passive heat from solar radiation (Sawka et al., 2013). Consequently, effective climate responsive design of urban green space is complex. For instance, the species and genotypes included in this study illustrate how trees with a higher BAI (e.g., *C. betulus* 'Fastigiata', *Q. robur* 'Fastigiata', *Acer platanoides* 'Globosum', *Corulys colurna* L., *Quercus palustris* Münchh., etc.) should not be planted too close to east-, south-, and west-facing facades or in very close proximity to places that will attract visitors during winter. Instead these species may prove adequate to incorporate and strategically position a bit further away in targeted spots where venturi effects occur or on north-facing street corners to buffer some of the highest wind speeds. As the results from this study indicated, the PET values were lower for *C. betulus* 'Fastigiata' than for *G. biloba* in the immediate leeward proximity of the tree row. However, *C. betulus* 'Fastigiata' increased the PET with 1.1°C in the center of the courtyard compared with *G. biloba* due to decreased wind speed and reduced wind chill effects.

This study is based on a relatively simple spatial layout, and in reality more complex spatial arrangements will occur. Therefore it may also be necessary to consider, in densely built-up areas where space is restricted, that it might not be economically feasible to align the entire street with a row of trees but rather to be selective in where and for which purposes certain species are planted.

Incorporating trees into urban planning and site-level design is increasingly recognized as a necessary step in successful sustainable urban development. Notable examples can be found in current environmental accreditation systems such as LEED (USGBC, 2014), the Sustainable Sites Initiative (SSI, 2009), and the BRE Environmental Assessment Method (BREEAM, 2014). The benefits of the urban forest and its contribution to a wide range of ecosystem services are recognized worldwide, and urban reforestation programs and cross-sector collaboration have often been initiated with the support and commitment from NGO's and charitable trusts (e.g., Plant One Million, 2015; England's Community Forests, 2015; Trees and Design Action Group, 2015; Urban Reforestation, 2015). However, discussion

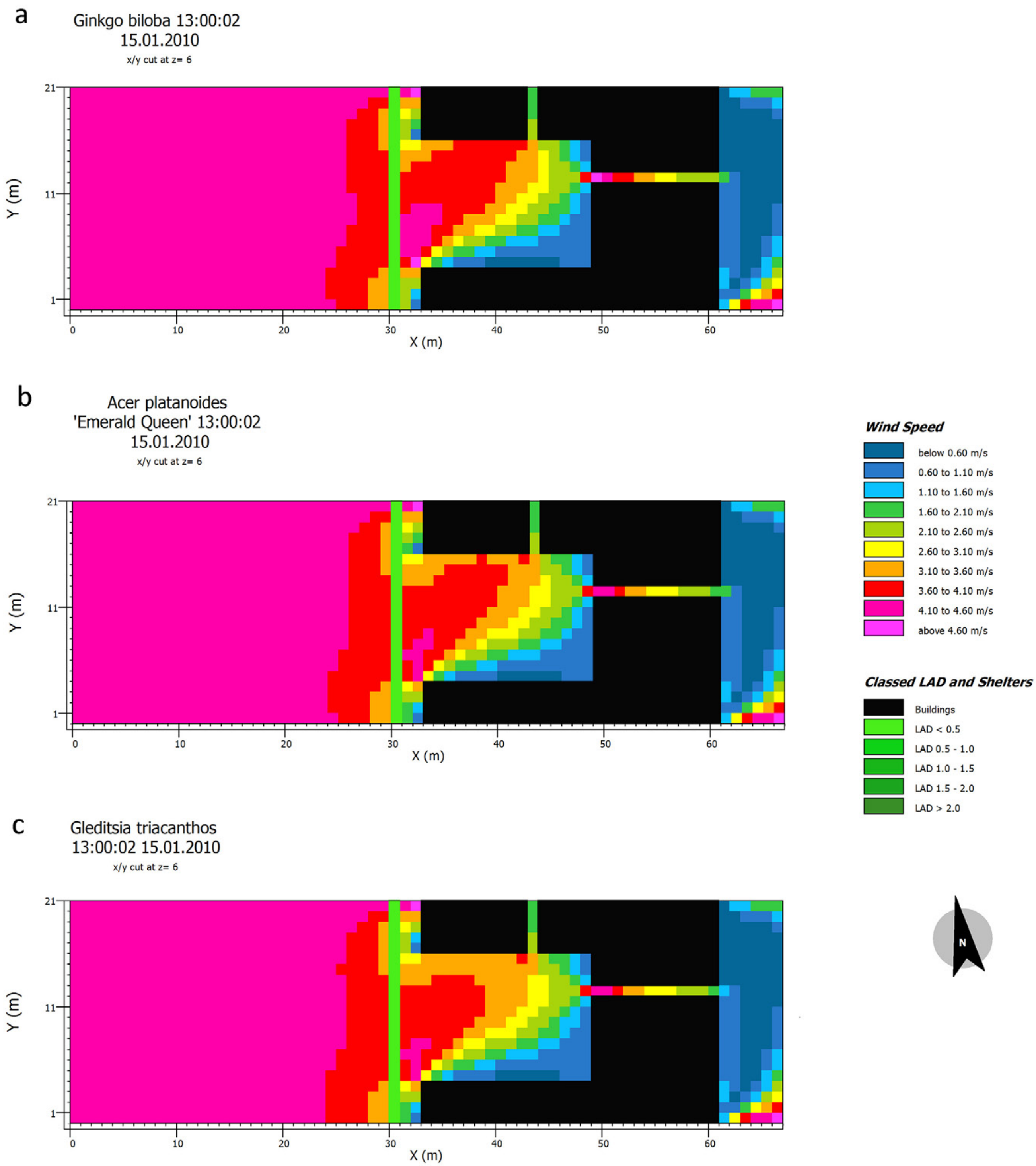

Fig. 5. Maps showing the wind speed pattern of simulated area in the microclimate model ENVI-met indicating the effect on wind speed and wind pattern at 4 m height from (a) *Ginkgo biloba* L., (b) *Acer platanoides* 'Emerald Queen', (c) *Gleditsia triacanthos* L., (d) *Quercus cerris* L., (e) *Corylus colurna* L., (f) *Carpinus betulus* 'Fastigiata', and (g) *Pinus strobus* 'Fastigiata'. The red and cerise fields indicate to wind speeds of 3.6 to >4.6 m s^{-1}, the green and orange fields indicate wind speeds of 1.6 to 3.6 m s^{-1}, and the blue fields illustrate areas of wind speeds of ≤1.60. LAD, leaf area density.

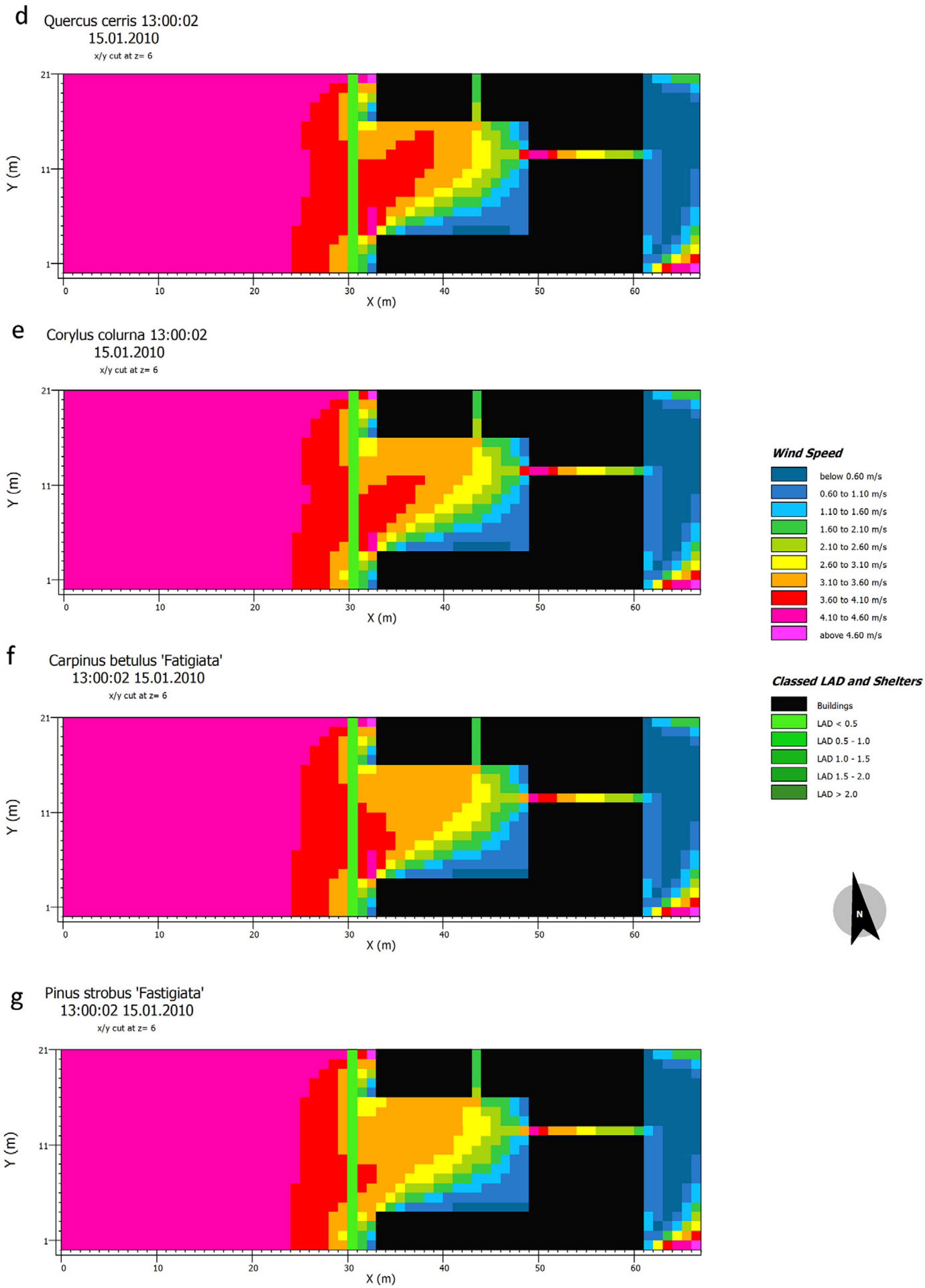

Fig. 5. Continued.

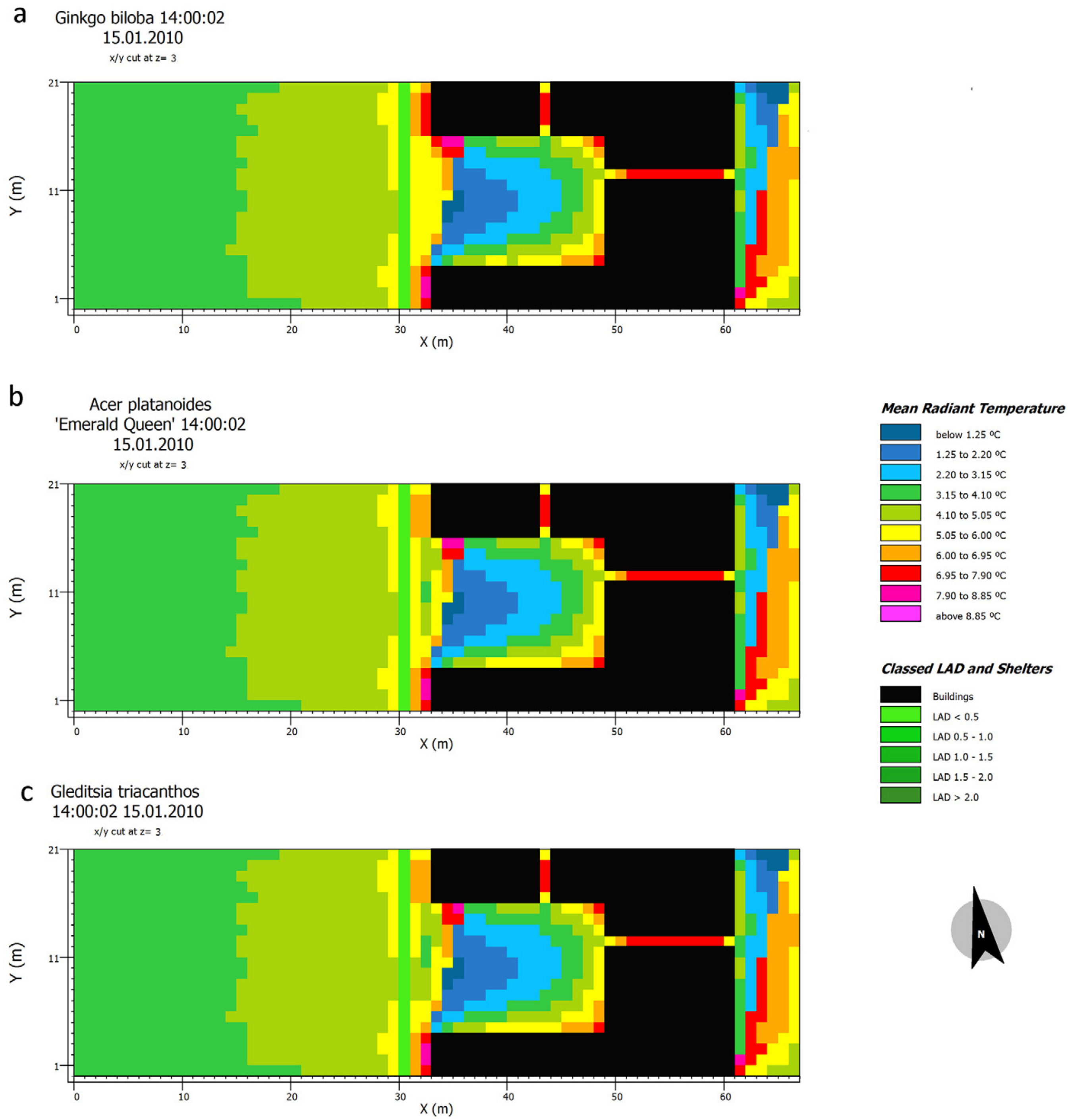

Fig. 6. Maps showing the mean radiant temperature (Tmrt) of the simulated area in the microclimate model ENVI-met indicating the effect on Tmrt at 1.20 m height from (a) *Ginkgo biloba* L., (b) *Acer platanoides* 'Emerald Queen', (c) *Gleditsia triacanthos* L., (d) *Quercus cerris* L., (e) *Corylus colurna* L., (f) *Carpinus betulus* 'Fastigiata', and (g) *Pinus strobus* 'Fastigiata'. The red and cerise fields indicate a Tmrt of 6.95 to >8.85°C, the green and orange fields indicate a Tmrt 3.15 to 6.95°C, and the blue fields indicate Tmrt ≤3.15°C. LAD, leaf area density.

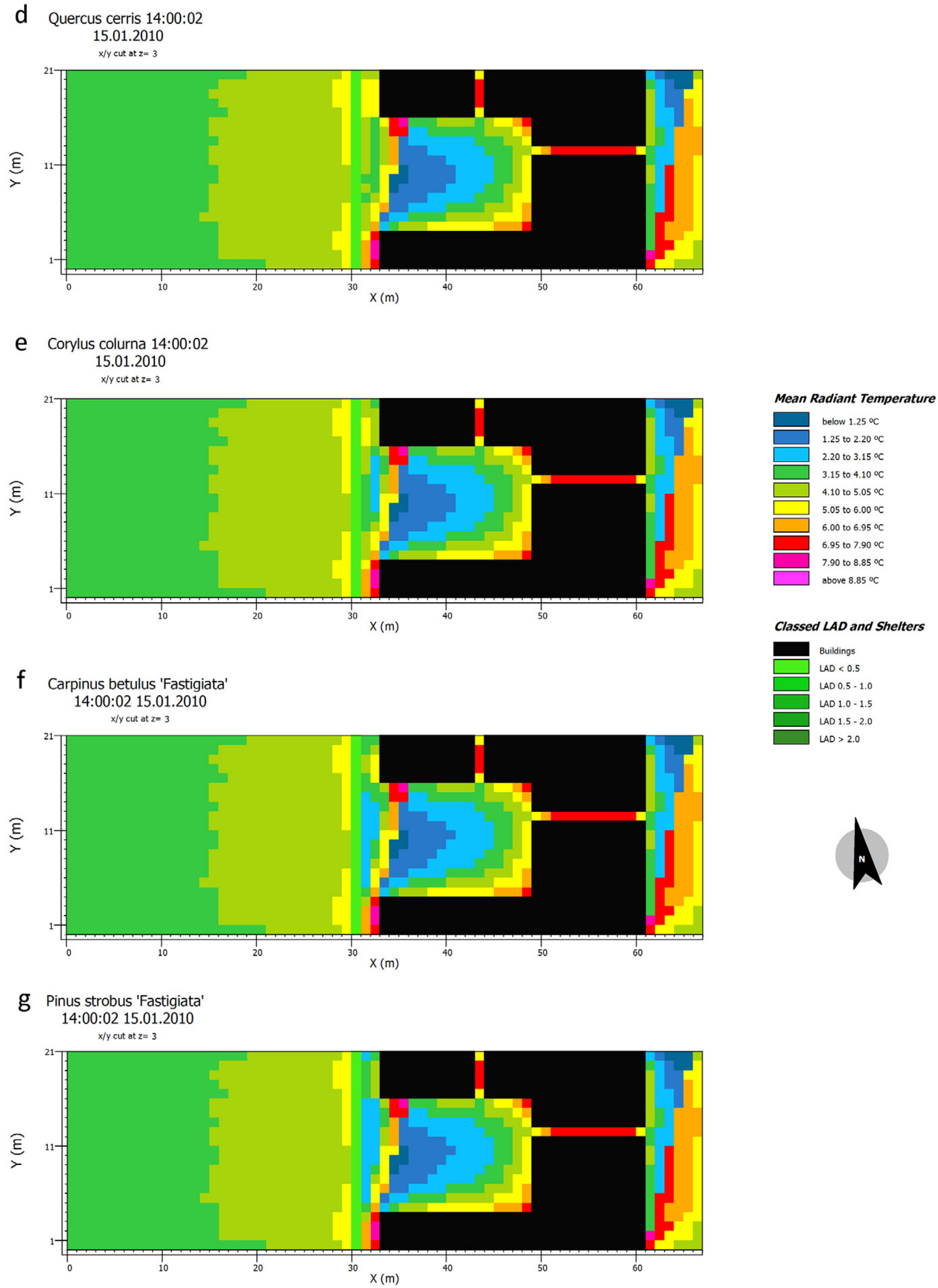

Fig. 6. Continued.

is limited regarding which species should be planted in the future urban forest. In urban areas subjected to infill development, it is vital that the limited space left over for green space is designed to deliver the greatest possible level of ecosystem services and multifunctional benefits. This requires an eco-technical understanding of which species are ecologically suited for the site as well as the species' characteristics that are likely to maximize the required ecosystem services. In temperate parts of the world, this includes planning and designing with both summer and winter seasons in mind.

Acknowledgments

The authors thank Oliver Bühler at Copenhagen University in Denmark for use of the Hørsholm Urban Tree Arboretum; Ann-Mari Fransson at the Swedish University of Agricultural Sciences, Sweden, for kindly lending the Digital Plant Canopy Imager (CI-110); and Erik Johansson at the Faculty of Engineering, Lund University, Sweden, for helpful support with queries relating to the ENVI-met 3.1 software.

References

Akbari, H., M. Pomerantz, and H. Taha. 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Sol. Energy 70:295–310. doi:10.1016/S0038-092X(00)00089-X

Ali-Toudert, F. 2005. Dependence of outdoor thermal comfort on street design in hot and dry climate. PhD thesis, Meteorological Institute MIF, Univ. of Freiburg.

Bitog, J.P., L. In-Bok, H. Hun-Seob, S. Meyong-Ho, H. Se-Woon, S. Il-Hwan, K. Kyeong-Seok, M. Ehab, and P. Zhenzhen. 2012. Numerical simulation study of a tree windbreak. Biosystems Eng. 111:40–48. doi:10.1016/j.biosystemseng.2011.10.006

BREEAM. 2014. BRE environmental assessment method. http://www.breeam.org/podpage.jsp?id=54 (accessed 12 Sept. 2014).

Breuer, L., K. Eckhardt, and H.-G. Frede. 2003. Plant parameter values for models in temperate climates. Ecol. Modell. 169:237–293. doi:10.1016/S0304-3800(03)00274-6

Brown, D.R., J. Vannos, N. Kenny, and S. Lenzholzer. 2015. Designing urban parks that ameliorate the effects of climate change. Landsc. Urban Plan. 138:118–131.

Bruse, M. 2009. ENVI-met 3.1 online manual. http://www.envi-met.com/ (accessed 14 July 2014).

Bruse, M., and H. Fleer. 1998. Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. Environ. Model. Softw. 13:373–384. doi:10.1016/S1364-8152(98)00042-5

Bühler, O., and P. Kristoffersen. 2009. The Urban Tree Arboretum in Hørsholm, Denmark: A new tool towards an improved education of arborists and tree managers. Urban For. Urban Green. 8:55–61. doi:10.1016/j.ufug.2008.10.001

Cantón, M.A., J.L. Cortegoso, and C. de Rosa. 1994. Solar permeability of urban trees in cities of western Argentina. Energy Build. 20:219–230. doi:10.1016/0378-7788(94)90025-6

CID Bio-Science. 2013. Plant Canopy Imager CI-110, Portable instruments for precision plant measurement, WA, USA. http://cid-inc.com/plant-canopy-analysis (accessed 14 Nov. 2014).

Cowett, F.D., and N.L. Bassuk. 2014. Statewide assessment of street trees in New York State, USA. Urban For. Urban Green. 13:213–220. doi:10.1016/j.ufug.2014.02.001

Dimoudi, A., and M. Nikolopoulou. 2003. Vegetation in the urban environment: Microclimatic analysis and benefits. Energy Build. 35:69–76. doi:10.1016/S0378-7788(02)00081-6

England's Community Forests. 2015. http://www.communityforest.org.uk/index.htm (accessed 15 Jan. 2015).

Fryd, O., S. Pauleit, and O. Bühler. 2011. The role of urban green space and trees in relation to climate change. CAB Rev. 6(053):1–18.

Gay, L.W., K.R. Knoerr, and M.O. Braaten. 1971. Solar radiation variability on the floor of a pine plantation. Agric. Meteorol. 8:39–60. doi:10.1016/0002-1571(71)90093-8

Gill, S.E., J.F. Handley, A.R. Ennos, and S. Pauleit. 2007. Adapting cities for climate change: The role of the green infrastructure. Built Environ. 33:115–133. doi:10.2148/benv.33.1.115

Hardy, J.P., R. Melloh, G. Koenig, D. Marks, A. Winstral, J.W. Pomeroy, and T. Link. 2004. Solar radiation transmission through conifer canopies. Agric. Meteorol. 126:257–270. doi:10.1016/j.agrformet.2004.06.012

Heisler, G.M. 1990. Mean wind speed below building height in residential neighborhoods with different tree densities. ASHRAE Trans. 96:1389–1396.

Johansson, E., J. Spangenberg, M. Lino Gouvêa, and E.D. Freitas. 2013. Scale-integrated atmospheric simulations to assess thermal comfort in different urban tissues in the warm humid summer of São Paulo, Brazil. Urban Clim. 6:24–43. doi:10.1016/j.uclim.2013.08.003

Konarska, J., F. Lindberg. A. Larsson, S. Thorsson, and B. Holmer. 2013. Transmissivity of solar radiation through crowns of single urban trees: Application for outdoor thermal comfort modelling. Theor. Appl. Climatol. 117:363–376. doi:10.1007/s00704-013-1000-3

Kontogianni, A., T. Tsitsoni, and G. Goudelis. 2011. An index for tree stability assessment in urban environment. Ecol. Eng. 37:914–919. doi:10.1016/j.ecoleng.2011.01.015

Kumakura, E., K. Nakaohkubo, and A. Hoyano. 2011. Numerical analysis of solar shading of a deciduous tree for seasonal change. In: M. Bodart and A. Evrard, editors, PLEA 2011 architecture & sustainable development, Vol. 2. 27th International Conference on Passive and Low Energy Architecture, Lovain-la-Neuve, Belgium, 13–15 July 2011. UCL Presses Universitaires de Louvain. p. 113–117.

Köppen, W. 2014. World Maps of Köppen-Geiger climate classification. http://koeppen-geiger.vu-wien.ac.at/present.htm (accessed 13 Nov. 2014).

Lenzhölzer, S. 2010. Designing atmospheres: Research and design for thermal comfort in Dutch urban squares. PhD thesis, Wageningen Univ., Wageningen, the Netherlands.

Lenzhölzer, S., and J. Koh. 2010. Immersed in microclimatic space: Microclimate experience and perception of spatial configurations in Dutch squares. Landsc. Urban Plan. 95:1–15. doi:10.1016/j.landurbplan.2009.10.013

Liakatas, A., N. Proutsos, and S. Alexandris. 2002. Optical properties affecting the radiant energy of an oak forest. Meteorol. Appl. 9:433–436. doi:10.1017/S135048270200405X

Matzarakis, A., F. Rutz, and H. Mayer. 2007. Modelling radiation fluxes in simple and complex environments: Application of the RayMan model. Int. J. Biometeorol. 51:323–334. doi:10.1007/s00484-006-0061-8

Matzarakis, A., F. Rutz, and H. Mayer. 2010. Modelling radiation fluxes in simple and complex environments: Basics of the RayMan model. Int. J. Biometeorol. 54:131–139. doi:10.1007/s00484-009-0261-0

Meteotest. 2010. Meteonorm version 6.1.0.21, December 2010. Meteotest, Bern.

Myneni, R.B., R.R. Nemani, and S.W. Running. 1997. Estimation of global leaf area index and absorbed par using radiative transfer models. IEEE Trans. Geosci. Remote Sens. 35:1380–1393. doi:10.1109/36.649788

Nikoofard, S., V.I. Ugursal, and I. Beausoleil-Morrison. 2011. Effect of external shading on household energy requirement for heating and cooling in Canada. Energy Build. 43:1627–1635. doi:10.1016/j.enbuild.2011.03.003

Nowak, D.J. 1996. Estimating leaf area and leaf biomass of open-grown deciduous urban trees. For. Sci. 42:504–507.

Oke, T.R. 1988. Street design and urban canopy layer climate. Energy Build. 11:103–113. doi:10.1016/0378-7788(88)90026-6

Peper, P. J., and E.G. McPherson. 2003. Evaluation of four methods for estimating leaf area of isolated trees. Urban Forestry Urban Greening 2:019–029.

Plant One Million. 2015. http://plantonemillion.org/ (accessed 15 Jan. 2015).

Santamouris, M. 2011. Energy and climate in the urban built environment. Routledge, New York.

Shashua-Bar, L., D. Pearlmutter, and E. Erell. 2011. The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. Int. J. Climatol. 31:1498–1506. doi:10.1002/joc.2177

Sawka, M., A.A. Millward, J. McKay, and M. Sarkovich. 2013. Growing summer energy conservation through residential tree planting. Landsc. Urban Plan. 113:1–9. doi:10.1016/j.landurbplan.2013.01.006

Sinclair, W.A., and H.H. Lyon. 2005. Diseases of trees and shrubs. 2nd ed. Cornell Univ. Press, Ithaca, NY.

Sjöman, H., J. Östberg, and O. Bühler. 2012. Diversity and distribution of the urban tree population in ten major Nordic cities. Urban For. Urban Green. 11:31–39. doi:10.1016/j.ufug.2011.09.004

Sustainable Sites Initiative (SSI). 2009. Guidelines and performance benchmarks. American Society of Landscape Architects, Lady Bird Johnson Wildflower Center, and United States Botanic Garden.

Thorsson, S., F. Lindberg, I. Eliasson, and B. Holmer. 2007. Different methods for estimating the mean radiant temperature in an outdoor urban setting. Int. J. Climatol. 27:1983–1993. doi:10.1002/joc.1537

Trees and Design Action Group. 2015. Trees in hard landscape: A guide for delivery. http://www.tdag.org.uk/uploads/4/2/8/0/4280686/tdag_trees-in-hard-landscapes_september_2014_colour.pdf (accessed 15 Jan. 2015).

Tubby, K.V., and J.F. Webber. 2010. Pests and diseases threatening urban trees under a changing climate. Forestry 83:451–459. doi:10.1093/forestry/cpq027

Urban Reforestation. 2015. http://www.urbanreforestation.com/contact/ (accessed 15 Jan. 2015).

USGBC. 2014. U.S. Green Building Council, Green Building Leadership (LEED). http://www.usgbc.org/leed (accessed 12 Sept. 2014).

Wang, J., T.A. Endreny, and D.J. Nowak. 2008. Mechanistic simulation of tree effects in an urban water balance model. J. Am. Water Resour. Assoc. 44:75–85. doi:10.1111/j.1752-1688.2007.00139.x

Westerberg, U., and M. Glaumann. 1990–1991. Design criteria for solar access and wind shelter in the outdoor environment. Energy Build. 15(3–4):425–431. doi:10.1016/0378-7788(90)90017-D

Xiao, Q., and E.G. McPherson. 2002. Rainfall interception by Santa Monica's municipal urban forest. Urban Ecosyst. 6:291–302. doi:10.1023/B:UECO.0000004828.05143.67