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Hunting for a Larger Diversity of Urban Trees in Western Europe—A Case Study from the Southern Caucasus

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Abstract. The primary aim of this study was to communicate a method for locating natural habitats where trees grows under conditions that are comparable to those in urban environments in terms of water stress. This is presented by analyzing five different forest reserves in the southern Caucasus (Republic of Georgia) where calculation of net water balance over the period of a year was conducted. This provided an insight into the drought at the sites during the growing season. The data were thereafter compared with similar calculations for five different cities in Western Europe in order to see if there were any matches in drought stress between the cities and the forest reserves. To extend the analysis, conditions in the five cities were assessed for high density and low density areas, and for the current climate and a future climate scenario. The comparisons revealed some matches between conditions in the forest reserves and those in different scenarios/areas in the cities. A secondary aim was to identify specific ecotypes in the wild demonstrating great potential to handle growing conditions similar to those in urban environments based on inventories of woody plants in the forest reserves. A total of 44 woody species were found in the forest reserve systems with a random distribution throughout the five study sites. Based on the commitments presented above a preliminary screening can be done where future tree selection focus can be directed towards highly promising species and ecotypes, which would undoubtedly limit the time lag before proper plant material can be released.

Keywords. Diversification; Ecosystem Services; Ecotypes; Tree Selection; Urban Forest; Urban Trees.

INTRODUCTION

With growing awareness of ecosystem services and the role of green infrastructure, trees are gaining recognition in research and in policy making as a means to deliver important structure and thus help to achieve resilience and sustainability in cities worldwide (Morgenroth et al. 2016; Pauleit et al. 2017). However, urban trees in streets and parks are facing several challenges where a changing climate, threats of insect attacks and diseases, and highly paved and often compact growing conditions create difficult situations (Sjöman et al. 2012a). One of the most effective means of mitigating these problems is to increase the diversity of tree species across the urban landscape (e.g., Hooper et al. 2005; Alvey 2006). With increased diversity, the likelihood of healthy, strongly growing and maturing trees also increases, and thereby the expected provision of ecosystem services improves (Gómez-Muñoz et al. 2010). Still, many cities rely on only a few species within their entire tree population (e.g., Cowett and Bassuk 2014; Kendal et al. 2014; Sjöman et al. 2012b; Yang et al. 2012; Raupp et al. 2006). This undoubtedly decreases the resilience of the urban forest system in the event of extreme weather or pest invasion. Furthermore, ways of diversifying the urban forest are compromised by a lack of knowledge regarding unknown species, including within the profession of urban tree planners and the nursery industry. In order to create confidence within the landscape profession to produce and employ unconventional species, tangible information needs to be available. Moreover, this information needs to be obtained in an iterative and pragmatic research approach. This paper exemplifies and discusses one such approach using a case study from the southern Caucasus (Republic of Georgia).

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Urban Tree Diversity

In attempts at making the urban forest more diversified in its species makeup, an important consideration that is often overlooked is the value of choosing species with the right adaptation qualities. Simply ordering new tree species and genotypes that are untested for the region is not appropriate, as careful testing of adaptability and longevity in stressful urban habitats must weigh heavily in the selection (Raupp et al. 2006). Poor or incorrect choices may result in increased mortality, reduced lifespan, and ultimately greater costs when failed or failing trees must be removed or replaced (Tello et al. 2005; Raupp et al. 2006). Important information to consider is the origin of the species, in order to assess whether the provenance matches the site climate and to secure winter hardiness. Another determinant is the kind of ecosystem from which the genetic material originates, which may reflect its capacity for different growing habitats. An illustrative example of this is given in a study by Bauerle et al. (2003), where a selection of red maple (*Acer rubrum*), originating from dry habitats, showed significant capacity to withstand dry conditions in urban areas compared with genotypes originating from wet habitats. In a recent evaluation by Sjöman et al. (2015), different genotypes of red maple and sugar maple (*A. saccharum*) showed marked differences when turgor loss point was used to rank drought tolerance. This indicates that it is not possible to treat a whole species group as either sensitive or tolerant to e.g., water stress, since tolerance in this regard can differ widely between different genotypes. This is especially the case for species covering a wide natural distribution and growing in different climates and site conditions.

As regards the tree species most commonly used in cities today, there is a substantial understanding of the capacity and limits of their tolerance to various stresses depending on species and genotype (e.g., Trowbridge and Bassuk 2004; Dirr 2009). However, this understanding is much more incomplete as regards rare or unconventional species and genotypes, where new perspectives are highly needed. A rather new approach is to use the concept of locally adapted ecotypes, as suggested in a review by Mijnsbrugge et al. (2010). This method can assist in finding appropriate ecological traits and characteristics in different species and genotypes correlating to challenging urban situations where water stress is common. This also introduces new plant hunting profiles, where new and alternative species can be targeted in order to increase knowledge of specific traits dependent on varying growing conditions. Arboreta and botanical gardens offer a sound platform for such studies, where correlations can be made to analyze the potential of specimens for urban paved environments. Such analyses can include specific leaf area and wood density (e.g., Greenwood et al. 2017), plant vulnerability to cavitation (e.g., Cochard et al. 2013), and determinants of leaf turgor loss point (e.g., Bartlett et al. 2012), which provide a solid base to analyze water stress and various means to cope with drought. However, the genetic plant material in the tree collections of botanical gardens may not be the best assortment when selecting species for dry urban sites, since the best genetic material may still be out in the wild. In the plant hunting literature with the focus on trees, attention to date has mainly been botanical, i.e., introducing new species to science, and horticultural, i.e. introducing species with extraordinary flowers, autumn color, leaf texture, trunk structure, etc. (e.g., Musgrave et al. 1998; Lancaster 2008; Kilpatrick 2014). Past interest in finding trees tolerant to the various stresses that occur in urban environments has been almost non-existent. This gives the impression that, when analyzing plant material from famous tree collections such as Gothenburg Botanical Garden in Sweden, Kew Gardens in London, UK, or Arnold Arboretum in Boston, U.S.A., the best genetic material is not being analyzed. Therefore, new approaches where stress tolerance and capacity for delivering ecosystem services are included in the plant hunting process, together with traditional horticultural and botanical interests, are needed to search for future urban trees.

Aim of the Study

The aim of this study was two-fold. The primary aim was to devise and assess a method for locating natural habitats where trees grow under conditions that are comparable to those in urban environments in terms of water stress. A secondary aim was to identify specific ecotypes in the wild demonstrating great potential to handle growing conditions similar to those in urban environments based on the natural habitats identified in step one. These aims were pursued in a case study of five forest reserves in the southern Caucasus (Republic of Georgia), where calculations of water net differences and forest inventories were carried out in order to assess the potential for locating

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alternative species for future use in urban environments in Western Europe. The study forms part of a research program initiated by the Swedish University of Agricultural Sciences and Gothenburg Botanical Garden, Sweden. Other case study areas are located in the Qinling Mountains, China (Sjöman et al. 2010), and the Steppe forests of eastern Romania and the Republic of Moldova (Sjöman et al. 2012c).

The underlying hypothesis in this research program is that alternative tree species for urban use can be identified through studies of natural habitats where trees are exposed to stresses similar to those in urban paved environments. From the perspective of northern and western parts of Central Europe and adjoining milder parts of Northern Europe (in the following abbreviated to "the CNE region"), it is unlikely that the species-poor native dendroflora can provide a large range of tree species with extended tolerance to the environmental stresses typical of paved sites in urban situations (Sjöman et al. 2016). However, regions with a comparable climate, but with a rich dendroflora, may have the potential to provide new tree species and genera for this purpose (Breckle 2002; Roloff et al. 2009).

MATERIAL AND METHODS

Study Area

The Republic of Georgia displays rather contrasting conditions in terms of climate, precipitation, and site conditions. This in turn accounts for the high number of plant communities within this comparatively small territory (Nakhutsrishvili 2013). The mountain region of the Caucasus (including the minor Caucasus in the south) occupies an interesting geobotanical position due to altitude and large differences in microclimates, such as between south- and north-facing slopes (Breckle 2002). Vegetation systems range from high alpine plant communities to large areas of steppe and steppe forests at lower altitudes (Nakhutsrishvili 2013). In many of these systems, trees are exposed to a warm, dry summer climate and winter temperatures similar to those in inner city environments in the CNE region (Breckle 2002).

In order to study vegetation systems with similar climate and growing conditions to those in urban environments in Western Europe, the mild and moist climate in the western part of the Republic of Georgia was excluded. Instead, the research focus was directed towards the more continental regions, including central and eastern parts of the country. Due to the strong influence of humans and related agriculture and forestry, it was difficult to get an overview of the natural composition of species and the structural arrangement of the indigenous forest stands. Therefore, the study was conducted in five different forest reserves with minimum human impact: Akhmeta (Babaneuri Nature Reserve), Bakuriani (Ktsia-Tabatskuri Forest Reserve), Kutaisi (Ajameti Forest Reserve), Mtskheta (Tbilisi National Park), and Oni (Racha-Lechkhum-Kvemo Forest Reserve) (Figure 1). The selected forest reserves represent clear climatic differences, which makes it possible to test the methodology for the

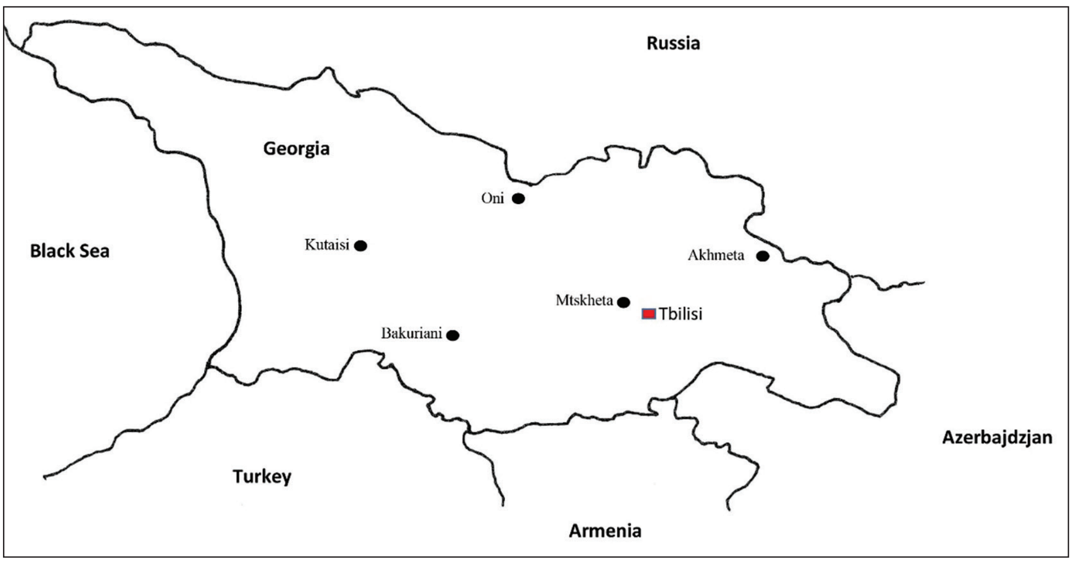

Figure 1. Location of the different forest reserve study sites in Georgia located in black.

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study evaluating site matches or differences to urban environments in Western Europe when calculating potential water net differences. The five forest reserves represent isolated cases, and based on the result further regions can be identified for future evaluations in the southern Caucasus.

Calculation of Potential Water Stress

Since water stress is the main problem for urban trees (e.g., Craul 1999; Sieghardt et al. 2005), the potential water stress (net water difference) in the study plots was calculated. Through these calculations, is it possible to view the water balance over the year where loss of water through evapotranspiration is compared with precipitation, which gives indications when a water stress during the season will occur and how extensive it will be. In calculating potential evapotranspiration, the regression presented by Thornthwaite (1948) was used, with monthly potential evapotranspiration based on the values of temperature, number of sunshine hours per day, water runoff, and cloudiness (Sjöman and Richnau 2009). Sunshine hours per day were estimated on a monthly basis (Meeus 1991), while days with rainfall were used as an indicator of cloudiness. The climate data for the five forest reserves were obtained from the National Environmental Agency of the Ministry of Environment Protection and Natural Resources in Tbilisi, Republic of Georgia (http://www.nea.gov.ge) (Table 1).

Table 1. Mean monthly temperature (° C) and precipitation (mm) in the field study areas.

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual mean[a]
Akhmeta— 430 MASL[b]													
Mean monthly temp. (° C)	0.4	1.5	6.0	12.4	16.9	21.1	21.1	23.7	19.4	13.5	7.1	2.0	M = 20.4
Precipitation (mm)	19.6	23.6	33.3	53.2	76.0	85.6	76.9	70.2	47.0	42.1	32.2	21.2	S = 355.6
Bakuriani— 2100 MASL													
Mean monthly temp. (° C)	-5.8	-5.0	-0.6	5.5	10.0	13.9	13.9	16.8	12.8	7.2	1.0	-3.9	M = 5.5
Precipitation (mm)	56.3	54.4	60.1	72.4	90.4	103.9	79.6	65.8	56.0	64.1	61.8	53.0	S = 395.8
Kutaisi— 117 MASL													
Mean monthly temp. (° C)	3.4	4.3	8.4	14.5	19.1	22.7	22.7	25.8	21.8	16.4	10.2	5.1	M = 22.4
Precipitation (mm)	113.0	96.0	101.7	99.2	96.2	109.8	83.1	78.1	102.4	126.1	124.2	120.4	S = 469.6
Mtskheta— 629 MASL													
Mean monthly temp. (° C)	0.9	1.8	6.3	12.5	17.0	21.1	21.1	23.7	19.6	13.9	7.6	2.6	M = 20.5
Precipitation (mm)	20.1	23.6	31.7	51.0	73.4	68.3	46.4	41.9	35.6	39.3	30.5	21.4	S = 265.5
Oni— 1190 MASL													
Mean monthly temp. (° C)	1.1	2.2	6.6	12.9	17.6	21.5	21.5	24.2	20.1	14.3	7.7	2.6	M = 21.0
Precipitation (mm)	55.9	47.7	54.3	65.6	69.7	74.8	61.4	55.8	54.8	65.8	63.4	57.5	S = 316.5

[a] Mean annual temperature (M) and cumulative precipitation (S) in the respective area.
[b] Meters Above Sea Level

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The potential evapotranspiration (or reference evapotranspiration, mm per month) for a typical month of 30 days with a 12-h photoperiod/day was modeled with an average temperature (T, °C) using the scheme proposed by Thornthwaite (1948) and modified by Pereira and Pruitt (2004) as:

$$ET_M = 16\left(10\frac{T}{I}\right)^a, 0^oC \le T \le 20^oC$$

where I is a thermal index imposed by the local normal climate temperature regime (T_n, °C) and the exponent a is a function of I, both computed by:

$$I = \sum_{n=1}^{12}(0.2T_n)^{1.514}, T_n > 0^oC$$

For temperatures above 26° C, the equation of Willmott et al. (1985) was used, in which ET_M is represented as:

$$a = 6.75\ x\ 10^{-7}I^3 - 7.71\ x\ 10^{-5}I^2 + 1.7912\ x\ 10^{-2}I + 0.49239$$

In order to convert the estimates from a standard monthly (ET_M, mm per month) to a daily time scale (ET_D, mm per day), the following correction factor (C) was used:

$$ET_M = -415.85 + 32.24T - 0.43T^2, T > 26^oC$$

where N is the photoperiod (h) for a given day.

$$C = \frac{N}{360}$$

Estimates of water run-off for the five forest reserves studied were based on P90 (2004) with an assumed 10% run-off.

In order to examine the potential usefulness of the forest reserves and their tree species for urban environments in the CNE region, the evapotranspiration estimates calculated for the reserves were compared with similar estimates for five cities throughout Western Europe that all represent rather different climates. These were Madrid (Spain), London (UK), Berlin (Germany), Copenhagen (Denmark), and Stockholm (Sweden). Climate data for the cities were taken from the websites of the Swedish Meteorological and Hydrological Institute (SMHI) (https://www.smhi.se/en) and the Danish Meteorological Institute (DMI) (http://www.dmi.dk/en/vejr) (Table 2). Based on studies of urban morphology types by Gill (2006) and Deak Sjöman and Gill (2014), two different site situations were assessed: (1) high density urban areas (where impermeable materials account for 79% of area); and (2) low density urban areas (where impermeable materials account for 43% of area). These two site situations were analyzed as regards: 1) the present climate and 2) a future climate scenario. For the CNE region, future climate scenarios predict an average increase of 2 to 6° C (3.6 to 10.8° F) in temperature, combined with more frequent heatwaves and periods of drought during summer (Gill et al. 2007; SOU 2007; IPCC 2014). In this study, a mean increase of 3° C (5.4° F) was assumed.

Field Measurements

In each forest reserve, five separate plots (30 m × 30 m [98 feet × 98 feet]) were established, resulting in a total of 25 plots with an allocated area of 4500 m^2 (48,437.6 feet^2). These plots were strategically placed within recognized forest stands, with particular attention to areas with mature forests and homogeneous site conditions.

All woody species at the forest reserve study sites were inventoried and classified into three different categories depending on the vertical distribution: upper canopy layer (UCL), lower canopy layer (LCL), and shrub level (SL) with plants < 1.5 m (5 feet). This classification helped delineate the tolerance to warm and dry habitats depending on the position of species within the forest structure. Trees in the canopy layer modify the wind, humidity, and temperature microclimate for species in the understory layer (Oliver and Larson 1996). Thus, canopy species experience much more effective transpiration due to the exposure to wind and sun.

In all study plots, the soil type, based on Urushadze and Ghambashidze (2013) and Urushadze et al. (2016), was identified by excavating 10 pits at random in each plot to a depth of 0.5 m (1.6 feet). Through this rough soil type determination, it was possible to draw qualitative conclusions on the water-holding capacity and make an assumption on available soil depth (Table 3).

RESULTS

Potential Water Stress in the Five Cities Under the Current Climate

Calculations of the potential water stress (evapotranspiration ETM, mm per month) in the five cities revealed

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Table 2. Mean monthly temperature (° C) and precipitation (mm) in Western European cities used for assessments.

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual mean[a]
Berlin													
Mean monthly temp. (° C)	0.5	1	4.5	8.5	13.5	16.5	18	17.5	14	9.5	4.5	1	M = 9.1
Precipitation (mm)	43	37	38	42	55	71	53	65	46	36	50	55	S = 591
Copenhagen													
Mean monthly temp. (° C)	3	3	7	9	14	18	19.5	19.5	16.5	12.5	8	5	M = 11.3
Precipitation (mm)	36	24	34	35	40	45	57	55	53	47	52	47	S = 525
London													
Mean monthly temp. (° C)	3.5	4	6	8	11	14.5	16.5	16	14	10.5	6.5	4.5	M = 9.6
Precipitation (mm)	78	51	61	54	55	57	45	56	68	73	77	79	S = 754
Madrid													
Mean monthly temp. (° C)	5.5	7.5	9.5	11.5	15.5	20.5	24.5	24	20.5	14.5	9.5	6.5	M = 14.1
Precipitation (mm)	33	34	23	39	47	26	11	12	24	39	48	48	S = 384
Stockholm													
Mean monthly temp. (° C)	-3	-3	0	5	11	16	17.5	16.5	12	7.5	3	-1	M = 6.8
Precipitation (mm)	39	27	26	30	30	45	72	66	55	50	53	46	S = 539

[a] Mean annual temperature (M) and cumulative precipitation (S) in the respective area.

clear differences in the amount of runoff produced in low density urban areas compared with high density areas. Under the current climate, high density urban areas in Madrid experience negative net water conditions already in February, while in low density areas, this occurs in May (Figure 2). In London, Berlin, and Copenhagen, negative net water occurs in April in high density areas, while Stockholm experiences a negative net water balance in May. Low density urban areas in Berlin, Copenhagen, and Stockholm experience negative net water in June, while in corresponding areas in London this occurs in July due to higher precipitation rate (Table 2).

Potential Water Stress in the Five Cities Under Future Climate Scenarios

On analyzing the cities in a future climate change scenario, it was found that a negative net water situation occurred one month earlier in low density urban areas in Copenhagen and Stockholm, while the other three cities experienced negative net water within the same period as at present, but with a more intense trend. In high density urban areas, negative net water occurred much earlier for all cities, but especially for Madrid, which risked experiencing negative net water levels already in January. In London, Berlin, and Copenhagen, it occurred in March, and in Stockholm in April (Figure 2).

Potential Water Stress in the Forest Reserve Systems

Analysis of the forest reserve systems in the Republic of Georgia revealed that both Akhmeta and Mtskheta experience a negative net water situation already in May with a noticeable increase during the following month (Figure 2). Bakuriani forest reserve is an

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Table 3. Total number of wooded species and their structural distribution in the study plots at the five different forest reserves, divided into three different categories depending on the vertical distribution: upper canopy layer (UCL), lower canopy layer (LCL), and shrub level (SL) with plants < 1.5 m.

Species	Akhmeta	Bakuriani	Kutaisi	Mtskheta	Oni
Abies nordmanniana	-	SL/LCL/UCL	-	-	SL/LCL/UCL
Acer campestre	SL	UCL	UCL	-	LCL
Acer cappadocicum	-	-	-	-	LCL
Acer platanoides	-	-	-	-	UCL
Acer trautvetteri	-	UCL	-	-	-
Carpinus betulus	UCL	LCL	UCL	-	LCL
Carpinus orientalis	LCL	-	LCL	SL/LCL/UCL	-
Castanea sativa	-	-	-	-	UCL
Celtis caucasica	-	-	-	UCL	-
Cornus mas	LCL	-	-	SL/LCL	-
Cornus sanguineum	SL	-	-	SL/LCL	-
Corylus avellana	-	SL/LCL	-	-	SL/LCL
Cotoneaster sp.	-	-	-	SL	-
Cotinus cogyggria	-	-	-	SL	-
Crataegus monogyna	SL/LCL	-	SL/LCL	-	-
Euonymus verrucosa	-	-	-	SL	-
Fagus orientalis	-	SL/LCL/UCL	-	-	SL/LCL/UCL
Fraxinus excelsior	SL	-	-	UCL	-
Ilex colchica	-	-	-	-	SL
Juniperus foetidissima	-	-	-	UCL	-
Juniperus excelsa	-	-	-	UCL	-
Juniperus oxycedrus	-	-	-	SL/LCL	-
Ligustrum vulgare	SL	-	-	SL	-
Lonicera caucasica	-	SL	-	-	-
Paliurus spina-christi	-	-	-	SL/LCL	-
Picea orientalis	-	LCL/UCL	-	-	LCL/UCL
Pinus sylvetris spp. *hamata*	-	UCL	-	-	-
Populus tremula	-	UCL	-	-	-
Prunus avium	UCL	-	UCL	-	-
Prunus cerasifera	-	-	-	SL	-
Prunus lauracersus	-	-	-	-	SL
Pyrus caucasica	-	UCL	-	-	-
Quercus colchica	UCL	-	UCL	UCL	-
Quercus hartwissiana	-	-	UCL	-	-
Quercus macranthera	-	UCL	-	-	-
Rhododendron luteum	-	SL	-	-	-
Rhododendron ponticum	-	SL	-	-	-
Ruscus ponticus	SL	-	SL	SL	-
Sorbus torminalis	-	-	UCL	-	-
Tilia begoniifolia	-	SL/LCL/UCL	-	-	SL/LCL/UCL
Ulmus glabra	UCL	UCL	-	-	LCL
Viburnum lantana	-	-	-	SL	SL
Viburnum opulus	-	SL	-	-	SL
Zelkova carpinifolia	UCL	-	UCL	-	-

exception in that it currently does not experience any negative net water situation due to cooler temperatures and higher levels of precipitation (Table 1). Despite a warmer climate compared with the other forest reserves studied, Kutaisi experiences a negative net water situation later, in July, due to high levels of precipitation. Oni also experiences a negative net water situation in July based on a cooler climate which influences the level of evapotranspiration (Table 1).

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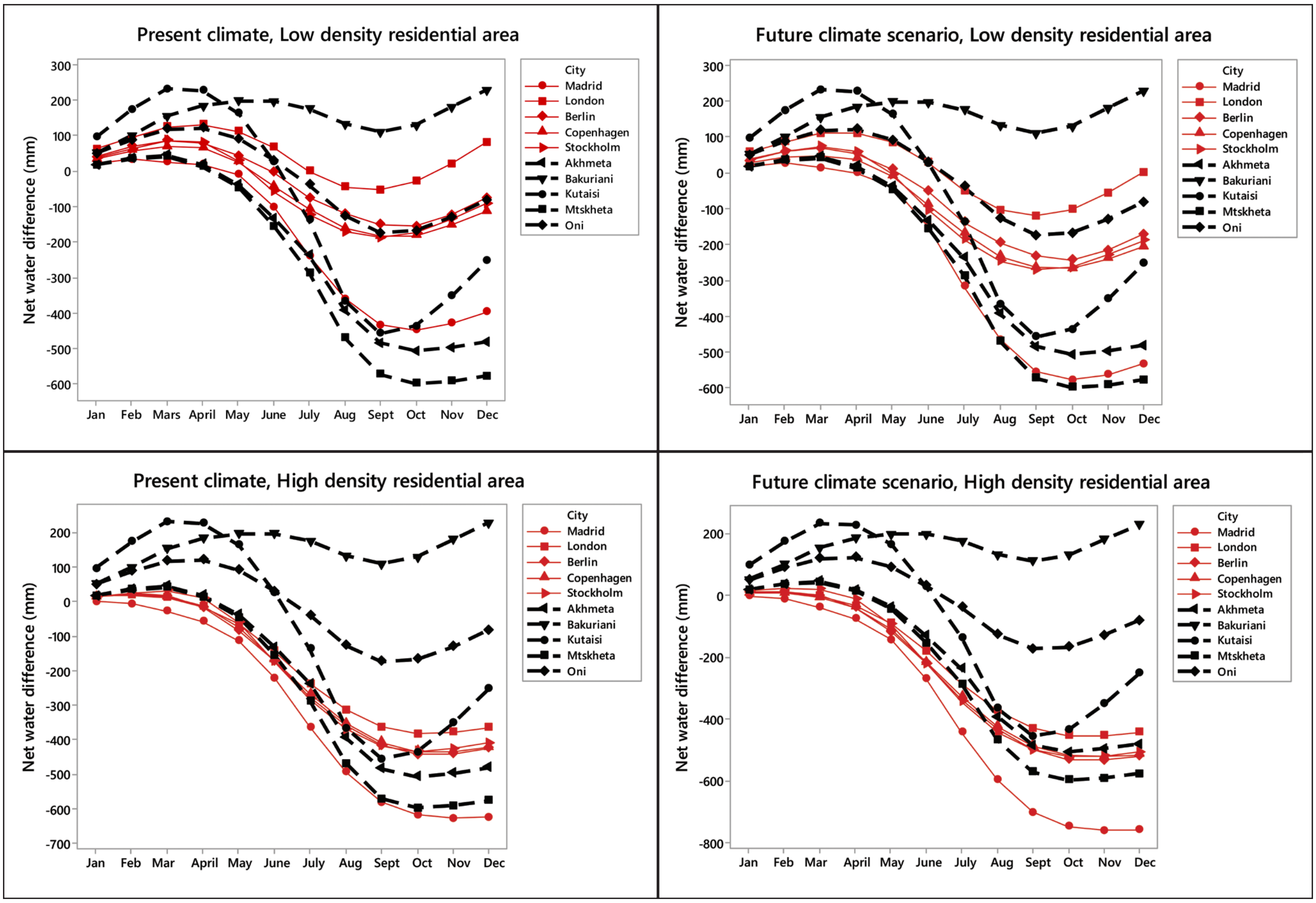

Figure 2. Calculated net water difference comparison between studied forest reserves and five West European cities presented in four different scenarios: i) present climate in low density residential area; ii) present climate in high density residential area; iii) future climate scenario in low density residential area; and, iv) future climate scenario in high density residential area.

Comparison of Conditions in the Forest Systems and in Urban Environments

On comparing the net water data for the five forest systems in Georgia with the five cities in Western Europe, it was possible to detect four groups with strong similarities, with one exception (Bakuriani) because it does not experience negative net balance (Figure 3). Comparison of the current climate in the individual cities with that in the forest systems revealed a clear match between low density urban areas in Madrid and Akhmeta forest reserve. A similar match with Akhmeta was obtained for high density urban areas in Berlin, Copenhagen, and Stockholm. A match was also found between low density areas in London and Oni forest reserve in spring, whereas in summer Oni experiences a much more intensely negative net water level. High density areas in London currently have a much faster and more intense negative net water situation throughout the year and show a closer match to Akhmeta (Figure 2).

In the assumed future climate change scenario, all cities experienced increased levels of negative net water balance. This made low density areas in London a closer match with Oni, while high density areas in London were a closer match with Akhmeta, as were high density areas in Berlin, Copenhagen, and Stockholm (Figure 2). Low density areas of Madrid showed a closer match with Mtskheta in the future climate scenario, while the negative net water trend in high density Madrid was so great that there was no match among the forests studied.

Field Inventory

The soil classification in the forest reserve plots indicated some variation with regard to water-holding capacity. The soil in Bakuriani, Kutaisi, and Oni is a loamy clay, while Akhmeta and Mtskheta have a drier

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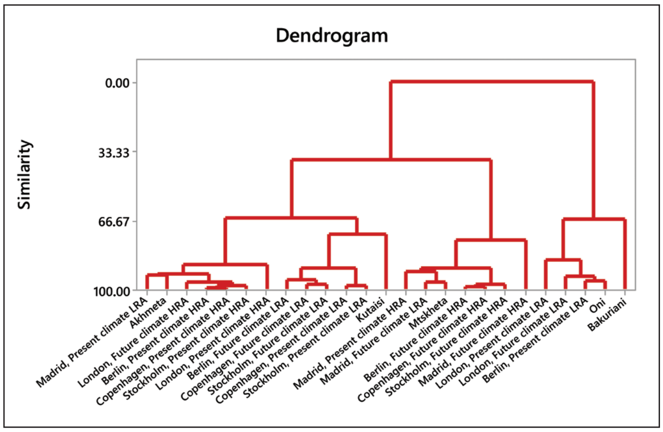

Figure 3. Dendrogram illustrating the site match between the natural and urban sites.

soil with sandy loam as the dominant texture (Table 4). It proved possible to excavate to 50 cm (19.5 in) depth in all sample pits, indicating no shallow soil profiles.

A total of 44 woody species were found in the forest reserve systems with a random distribution throughout the five study sites. *Acer campestre* and *Carpinus betulus* (syn. *C. caucasica*) were found at four sites (Table 3). On analyzing the structural distribution of the species, it was possible to detect pioneer species in the upper canopy layer (UCL) where they are exposed to an effective transpiration. This is intensified at the warmer sites of Akhmeta and Mtskheta. Species that were mainly found in the UCL in these two forest reserves, and thus experience a much more intensely negative net water situation over the year, are *Celtis caucasica, Carpinus betulus, Quercus colchica, Ulmus glabra*, and *Zelkova carpinifolia* (Table 3).

Species present in all layers, i.e., UCL, LCL, and SL, indicate a more late successional strategy with a pronounced tolerance for shaded conditions. At warmer and drier sites, where the differences between exposed conditions and the protected microclimate beneath the tree canopy is much more distinct, the number of species present in all layers in the forest reserves studied was found to be limited, with the one exception of *Carpinus orientalis* in Mtskheta. In cooler and moister forest systems, such as Oni and Bakuriani, the number of late successional species within all structural levels is higher and includes species such as *Abies nordmanniana, Fagus orientalis, Picea orientalis*, and *Tilia begoniifolia* (Table 3).

DISCUSSION

There is an urgent need to introduce a larger diversity of trees in urban areas due to current and future threats of diseases and/or insect attacks to urban tree populations, and thus using rare or non-traditional trees in modern cities is inevitable. However, there is an unwillingness among tree planners and landscape architects to take the risk associated with using non-traditional plant material due to lack of experience of novel species and limited information on their tolerance to different urban planting sites. Another limitation is the availability of suitable genetic material of tree species in nurseries (Sydnor et al. 2010). Moreover, it is unclear whether tree species available e.g., at a German nursery would be suitable for e.g., Stockholm

Table 4. Soil type determination in studied forest reserves.

Study site	Soil type	Description[1]
Akhmeta	Cinnamonic (Cambisols cromic)	Sandy loam, weakly alkaline or neutral reaction, moderate content of humus, deep penetration of humus
Bakuriani	Leptosols	Loamy clay, acid and weakly acid reaction, high content of humus, deep penetration of humus
Kutaisi	Alluvial (Fluvisols)	Loamy clay, weakly alkaline or neutral reaction, moderate content of humus, deep penetration of humus
Mtskheta	Cinnamonic (Cambisols chromic)	Sandy loam, weakly alkaline or neutral reaction, moderate content of humus, deep penetration of humus
Oni	Leptosols	Loamy clay, acid and weakly acid reaction, high content of humus, deep penetration of humus

[1]Based on Urushadze and Ghambashidze 2013 and Urushadze et al. 2016.

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regarding winter hardiness and tolerance to challenging urban environments. As mentioned earlier, there is clear evidence that knowledge of the ecological background of species is of great importance in identifying their potential areas of use. If a specific ecotype originates from a warm, dry habitat, it is likely that its tolerance for these conditions will persist at other cultivation sites. This means that greater attention should be paid to the habitat and climate from which plant material originates, information seldom presented in nursery catalogues. The overall aim in the present study was to detect "new" tree species or ecotypes for urban environments by first identifying natural habitats where trees have been exposed to similar site conditions as in urban environments, i.e., warm and dry habitats. Sjöman et al. (2012a) used a similar selection approach based on two case studies in China and Romania/Republic of Moldova. In that case, four different steps were followed: i) identification of floristically rich regions based on climate data and matching inner-city environments; ii) identification of habitats similar to inner-city environments and evaluation of similarities with urban sites; iii) dendroecological studies to evaluate species growth; and iv) development in these habitats and collection of seeds from candidate trees in the habitats in order to obtain proper ecotypes.

In the present study in the Republic of Georgia, we followed the first two steps in this selection approach to identify natural habitats that matched urban habitats in the CNE region. A pragmatic selection approach was applied, with the focus on identification of plant material from natural habitats for use in high density urban situations in the CNE region. We analyzed five different forest reserves in the Republic of Georgia and calculated potential evapotranspiration and net water balance over the year. This provided an insight into the drought risk at the sites during the growing season. We compared the results with those for five different cities in Western Europe in order to see if there were any matches in drought stress conditions between the cities and the forest reserves. To extend the analysis, conditions in the five cities were assessed for high density and low density areas and for the current climate and a future climate scenario with a predicted average temperature increase change of 3° C (5.4° F). The comparisons revealed some matches between conditions in the forest reserves and those in different scenarios/areas in the cities.

When trying to identify natural habitats with similar growing conditions to urban environments, it would be very difficult and time-consuming to establish meteorological stations randomly in mountainous regions and hope to find matching habitats. Since water stress is the main abiotic constraint for trees in urban environments (Sieghardt et al. 2005), and in many regions is likely to increase under future climate scenarios (Allen et al. 2010), we opted to calculate the potential water stress (net water difference) in the five forests studied, which gave a good overview of water use and water loss over the year. When analyzing regions that can host trees for inner-city environments, data on precipitation alone are not necessarily a good indicator of drought (van der Schrier et al. 2011). From the perspective of agriculture, drought is defined as conditions which lead to stunted growth or even wilting of crop plants. These involve persistently high levels of potential evapotranspiration (PET), where the crop is unable to maintain itself by extracting water from the soil, combined with low levels of soil moisture content (van der Schrier et al. 2011). The Irrigation and Drainage Paper 56 issued by the Food and Agriculture Organization (FAO) recommends that the reference evapotranspiration proposed by Allen et al. (1989) for the Penman-Monteith equation (Monteith 1965) be used for such calculations. However, while the validity of this recommendation has been confirmed in many climates, the need for many input variables makes the method difficult to use, since such complex climate data are rarely available for remote areas of developing regions, such as the countryside in the Republic of Georgia, which limits its widespread use (Pereira and Pruitt 2004). An alternative is the use of regional weather stations providing the necessary input data. However, weather stations require qualified personnel for operation and maintenance, while instrument calibration is not common practice due to the lack of standards, even in research centers (Pereira and Pruitt 2004). Consequently, large measurement errors are possible due to exposure and aging of the instruments. A much simpler alternative is the Thornthwaite scheme (Thornthwaite 1948), since it requires only temperature as input data. However, the Thornthwaite approach has been found to produce underestimates under arid conditions and overestimates in the equatorial humid climate of the Amazon region. The Pereira and Pruitt (2004) modification of the

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Thornthwaite scheme was therefore used in this study when matching site conditions in the five forest reserves in the Republic of Georgia with those in the selected five large cities in Western Europe. This modification involves estimating daily reference evapotranspiration taking as input the normal climate temperature for determining the *I* and *a* thermal indices, and has a performance almost identical to that of the more robust and highly recommended Penman-Monteith FAO-56 model (PM-56) despite including fewer variables (Pereira and Pruitt 2004). When screening regions that can host potential urban trees for Western Europe, such simple and easy models that enable many large areas to be screened are needed.

Through our water net calculations, it was possible to detect suitable tree species not only for a specific city, but also for a specific urban site situation. A greater catalogue of suitable tree species is needed for street environments than park environments due to the much more constricted growing conditions in urban streets. Our calculation approach makes it possible to pinpoint a specific use category when analyzing forest systems. This is likely to be helpful and save much time in the subsequent selection process where the focus is on highly promising species/genotypes, rather than randomly selecting species without this additional information. The present compilation of water net differences in five forest reserves is far from providing a complete overview of the Republic of Georgia's potential as a source of trees for urban environments. However, from this study it was possible to identify specific region and climate types that are a close match to those in paved environments in Copenhagen, Denmark, which makes it easy to recognize further regions and sites of interest.

Carpinus betulus was found in both Oni and Akhmeta forest reserves, but the differing conditions in these two reserves indicate different use capacity of the species. Earlier research by Bauerle et al. (2003) and Sjöman et al. (2015) has shown that there are great differences in drought tolerance between different genotypes and ecotypes of different climate and site origins. *Carpinus betulus* is exposed to much warmer and drier conditions in Akhmeta than in Oni, so the potential of the Akhmeta ecotypes as an urban street tree can be assumed to be much higher than that of the ecotype from Oni.

This study should be regarded as a first step in a long chain of efforts before the proposed trees are released to the market. The test period, combined with production and evaluation, can take a long time, as it has to cover aspects such as evaluation of the species/genotypes capacity for different growing sites, propagation issues, establishment conditions, early maintenance demands, etc. However, the majority of the species found in Georgian forest reserves in the present study (Table 3) are not new to horticulture in Western Europe and North America, as they can all be found in nursery production and/or in tree collections. From these nurseries and plant collections, there is already a rather good knowledge of their propagation, establishment and maintenance needs, mature size, etc. Using this existing knowledge can make the selection process much shorter once proper ecotypes from the forest reserves are available and tested (Sjöman et al. 2012a). Moreover, even if *Carpinus betulus* is a common species in cultivation in the CNE region where the genetic material originates from, a much more humid and cooler forest habitat in the region compared to the plant material in the study in Georgia means that even for a common species, an "upgrade" of its tolerance for challenging sites will be necessary in order to increase its use potential towards paved environments in a future climate. In contrast, there is a lack of experience in Western Europe and North America of cultivation of species from, e.g., China, which will lead to a much longer selection process due to the many aspects that need to be investigated before any trustworthy recommendations can be made. A shorter selection process would help meet the urgent need for a larger plant stock for urban environments.

Furthermore, while this study focused on finding tree species that are tolerant to warm and periodically dry habitats, i.e., typical growing conditions in paved urban areas, further technical solutions and design will be necessary in order to develop sustainable and long-lasting tree plantings, especially for a future climate. Measures that decrease water runoff and increase water infiltration will be needed, which means that combining stormwater management and tree planting will be absolutely essential in paved environments in a future climate. All trees investigated in forest reserves in this study have a generous rooting space (more than 50 cm [19.5 in] in depth), which is not the case in street environments. Thus in paved environments, trees experience faster and more severe drought than in natural habitats, which means that choice of tolerant tree species or ecotypes must

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be combined with good design of planting pits and the use of structural soils combined with stormwater management. The results from this study should thus be seen as a part of a holistic approach, where climate-oriented design and construction are of equal importance. Moreover, it is important to bear in mind that this study focuses on water stress, which is the main constraint for trees in urban environments and especially in paved environments. However, there are further constraints for trees in urban environments which are important to include in the selection process in order to create a sustainable tree population, such as pollution, high and low temperatures, and tolerance for flooding, since we can also expect heavy rain events with large and intense rainfall levels in a future climate. Tolerance for these stressors needs its own unique perspective and is not included in this study.

The next step in the research process from this study will be to collect ecotypes of the species identified that best match the conditions in the particular city for which they are intended. Since a diverse tree population for paved urban sites and high density residential areas is most urgently needed due to much more extreme growing conditions than in park environments; finding species that can develop into large, healthy trees at these tough sites should be prioritized. This makes areas such as Akhmeta and Mtskheta very interesting, especially for a future climate situation in Western Europe. Species such as *Carpinus orientalis, Celtis caucasica, Quercus colchica, Q. hartwissiana, Sorbus torminalis*, and *Zelkova carpinifolia* can be particularly significant, since they occur naturally in habitats where they are exposed to water stress regimes similar to those occurring in many dense cities. When desirable ecotypes have been collected and established, more detailed evaluations must be performed to determine specific leaf area and wood density (e.g., Greenwood et al. 2017), plant vulnerability to cavitation (e.g., Cochard et al. 2013), determinants of leaf turgor loss point (e.g., Bartlett et al. 2012), etc., as evidence of the plant material's capacity to cope with drought. These evaluations will need much more controlled environments, which impedes their implementation in the field. They will also be expensive and time consuming. However, if a preliminary screening of the potential of the plant materials for a specific site situation can be done prior to these evaluations, the focus can be directed towards highly promising species and ecotypes, which would undoubtedly will limit the time lag before they can be released to the market.

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Résumé. L'objectif premier de cette recherche était de partager une méthode de localiser des habitats naturels où les arbres croissent sous des conditions s'apparentant à celles rencontrées dans les environnements urbains sur le plan du stress hydrique. Cela est obtenu par l'analyse de cinq réserves forestières distinctes du Caucase sud (République de Géorgie), alors que le calcul du bilan hydrologique net sur une année a été mesuré. Nous obtînmes ainsi un aperçu de la sécheresse de ces sites durant la saison de croissance. Ces données furent par la suite comparées avec des mesures similaires provenant de cinq villes d'Europe de l'Ouest afin de vérifier l'éventualité d'une correspondance entre le stress de sécheresse des villes et celui des réserves forestières. En complément de l'analyse, les conditions des zones de haute et de basse densité furent évaluées pour les cinq villes, prenant également en compte le climat actuel ainsi qu'un scénario de climat évolutif. Les comparaisons révélèrent certaines adéquations entre les conditions dans les réserves forestières et celles de divers scénarios et zones municipales. Un objectif secondaire visait à identifier des écotypes spécifiques en milieu naturel démontrant un grand potentiel à supporter des conditions de croissances semblables à celles d'un environnement urbain sur la base d'inventaires des plantes ligneuses retrouvées dans les réserves forestières. Un nombre total de 44 espèces ligneuses fut identifié avec une répartition aléatoire parmi les cinq réserves forestières sous étude. Sur la base des engagements présentés ci-haut, une présélection peut désormais être effectuée afin que la priorisation du choix des essences soit orientée vers des essences et des écotypes très prometteurs, ce qui aura pour conséquence de réduire indubitablement le délai avant que des végétaux appropriés puissent être développés.

Zusammenfassung. Das primäre Ziel dieser Studie war, eine Methode zur Lokalisierung von natürlichen Habitaten zu kommunizieren, wo Bäume unter Bedingungen wachsen, die bezüglich ihres Wasserstresses vergleichbar mit urbanen Bedingungen sind. Das wird durch die Analyse von fünf verschiedenen Forstgebieten im südlichen Kaukasus (Georgien) dargestellt, wo die Kalkulation der Nettowasserbalance über eine Periode des Jahres durchgeführt wurde. Das lieferte eine Einsicht über die Trockenheit an diesen Standorten währen der Wachstumsperiode. Die Daten wurden hinterher mit ähnlichen Kalkulationen aus fünf verschiedenen Städten in Westeuropa verglichen, um zu sehen, ob es zwischen den Städten und den Forstgebieten bei der Trockenheit irgendwelche Ähnlichkeiten gibt. Um die Analyse auszudehnen, wurden die Bedingungen in den fünf Städten für Areale mit hoher und niedriger Dichte, das gegenwärtige Klima sowie ein zukünftiges Klimaszenario untersucht. Die vergleiche enthüllten ein paar Ähnlichkeiten zwischen den Bedingungen in den Forstgebieten und denen in verschiedenen Arealen in der Stadt. Ein zweites Ziel war die Identifikation spezifischer Ökotypen in der Wildnis, die das große Potential zur Bewältigung von Wachstumsbedingungen demonstrieren, die basierend auf den Inventuren der Gehölze in den Waldgebieten denen in urbaner Umgebung ähnlich sind. Insgesamt wurden 44 Gehölze in den Systemen der Forstgebiete gefunden, mit einer zufälligen Verteilung über die fünf Studienstandorte. Basierend auf den oben genannten Vorbedingungen kann ein screening angefertigt werden, wo der Fokus zukünftiger Baumselektionen in Richtung viel versprechender Spezies und Ökotypen geleitet werden kann,

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was zweifellos die Zeitspanne bis gutes Pflanzenmaterial zur Verfügung steht, reduzieren würde.

Resumen. El objetivo principal de este estudio fue comunicar un método para localizar hábitats naturales donde los árboles crecen en condiciones comparables a las de los entornos urbanos en términos de estrés hídrico. Esto es presentado analizando cinco reservas forestales diferentes en el sur del Cáucaso (República de Georgia), donde se realizó el cálculo del balance hídrico neto durante el año. Esto proporcionó una visión de la sequía en los sitios durante la temporada de crecimiento. Los datos se compararon posteriormente con cálculos similares para cinco ciudades diferentes en Europa occidental para ver si había coincidencias en el estrés por sequía entre las ciudades y las reservas forestales. Para ampliar el análisis, se evaluaron las condiciones en las cinco ciudades para áreas de alta densidad y baja densidad y para el clima actual y un escenario climático futuro. Las comparaciones revelaron algunas coincidencias entre las condiciones en las reservas forestales y aquellas en diferentes escenarios / áreas en las ciudades. Un objetivo secundario fue identificar ecotipos específicos en el medio silvestre que demostraran un gran potencial para manejar condiciones de crecimiento similares a las de los entornos urbanos basados en inventarios de plantas leñosas en las reservas forestales. Se encontró un total de 44 especies leñosas en los sistemas de reservas forestales con una distribución aleatoria en los cinco sitios de estudio. Sobre la base de los objetivos presentados, se puede realizar un examen preliminar en el que el enfoque de selección de árboles en el futuro puede dirigirse hacia especies y ecotipos altamente prometedores, lo que sin duda limitaría el retraso de tiempo antes de que se pueda liberar el material vegetal adecuado.

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