



The effect of urban morphology on *Tilia × europaea* flowering



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ABSTRACT

Urban planners need tools to manage urban growth without compromising the citizens' quality of life. Urban vegetation plays an important role in regulating local climate and improving air quality. Further, urban vegetation provides non quantifiable psychological and aesthetic benefits. On the other hand, vegetation also has negative impacts, such as allergen risk due to pollen dispersion. This paper investigates the effects of urbanization on tree phenology, exploring the intra-urban variability of *Tilia × europaea* L. flowering in Florence (Italy). Phenological observations were related to local air temperature, distance from the city center, impervious surfaces and building density. Data collected were used to test whether urban characteristics could be used to describe phenophase timing differences in the city. These differences are explained both by seasonal temperature variation as well as by impervious surface density. In fact *T. × europaea* flowering occurred first in the areas with a higher percentage of impervious surfaces. Both the start and end of flowering advanced by 1.4 days with a 10% increase in impervious surfaces. Our results suggest a potential application of the “impervious surfaces” urban morphology indicator to predict phenological shifts in an urban environment. These indicators can be processed by geographic information system tools to produce phenological maps of a specific urban area or future urban planning scenarios. This information can be used to improve the evaluation of the benefits and drawbacks of trees, such as their impact on local temperatures, the aesthetic improvement of the urban landscape or the negative effects on human health due to the risk of pollen allergy during the flowering period.

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Introduction

In a context where more than half of the world population is living in cities (United Nations, Department of Economic and Social Affairs, Population Division, 2012), the way in which urban areas are designed by urban planners becomes increasingly important. In fact, the urban planners should properly take into consideration the effects of urbanization on the environment and the quality of life of citizens in order to avoid the drawbacks of a rapid and uncontrolled growth of urban areas. The integration of up to date technology like geographic information systems (GIS), databases and environmental models can be integrated in a decision support system that can help policy makers in landscape and urban planning (Brett, 2003; Lindberg, 2007). Study of the relationship among several biological and urbanization variables employed to classify landscape and land cover was also made in West Georgia, to understand

ecosystem response to urbanization to be used as a land management and planning tool (Styers et al., 2010).

Usually, visual interpretation of aerial photography and spatial analysis of digital images are employed to characterize urban morphology (buildings, roads, trees, etc.) and can be effectively used to calculate indicators that can be used to evaluate the performance of the current urban environment or future urban planning scenarios (Gill et al., 2008; Mubareka et al., 2011; Van de Voorde et al., 2011; Nowak and Greenfield, 2012). Urban vegetation may play an important role in regulating the negative effects of extensive urbanization on local climate and human health (Tzoulas et al., 2007), and “the natural environment should be at the heart of urban design and management” (p. 83). A study by McPherson et al. (2011) investigated the benefits of planting 1000,000 trees in the city of Los Angeles, taking into consideration both quantitative indicators like energy savings, carbon sequestration, storm-water runoff reduction and aesthetic indicators like beauty, well-being and sense of place that can also cause differences in selling prices of properties with or without trees. Also street trees are very appreciated by people because they enhance the sense of well-being and people realize their importance especially when they experience a disturbance

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of the urban nature like a tree cut (Hunter, 2011). On the other hand, vegetation also has negative impacts, such as the management costs and, above all, the allergen risk due to pollen dispersion. Over recent years, many studies have investigated the effects of climate change and urbanization on plant phenology (e.g. Luo et al., 2007; Mimet et al., 2009; Jochner et al., 2012). As urbanization is associated with rises in temperatures and CO₂, urban climate conditions may be considered similar to future climate conditions and the urban environment may provide a low-cost alternative to current experimental methods by evaluating plant responses to climate change (Ziska et al., 2003; Mimet et al., 2009).

Air temperature appears to be the main climatic driver of plant phenology (Schleip et al., 2009; Wielgolaski, 2001). Some studies investigated the relationship between rising temperatures and the shift in phenological events both at European level (Menzel et al., 2006) and worldwide (Parmesan and Yohe, 2002). Other studies focused on the different response of plant phenology to urban and rural climate, and advanced flowering in urban environments due to the heat island effect is highlighted by many authors (e.g. Neil and Wu, 2006; Mimet et al., 2009; Neil et al., 2010).

The need to study the impact of urbanization on plant phenology at an intra-urban scale has recently been proposed by several authors (Mimet et al., 2009; Shochat et al., 2006). Owing to the complexity of the morphology of the urban environment, air temperature within the urban area may vary significantly (Oke, 1987; Petralli et al., 2011) and the size of green areas can affect both minimum and maximum temperature within 500 m distance (Petralli et al., 2013). The intra-urban thermal difference can have important consequences on plant phenological responses (Mimet et al., 2009; Ohashi et al., 2012). For example, flowering may start earlier in hotter areas than in cooler ones and as a result, the overall flowering period of the plants inside the city can take longer. Tree flowering can be seen as a phenomenon that improves the scenic quality of the urban landscape (Roy et al., 2012) or can be associated with negative effects on human health caused by a longer exposure of allergic subjects to airborne pollen (Cecchi et al., 2010). Therefore it would be useful if landscape planning and management tool also took into consideration the characteristics of the urban environment linked to the seasonal development of trees. The integration of the information on phenology in a decision support system could help assessing the performance of an urban transformation or an existing situation taking into consideration also benefits and drawbacks connected to the seasonal changes of urban landscape and their effects on human health.

One of the aims of this paper was to investigate whether local thermal regimes could be used to analyze the start and end of flowering variability of *Tilia × europaea* in the city of Florence.

This tree has a great traditional, historical and cultural importance in many countries in Europe, where it is widely distributed (Pigott, 1991). *Tilia* is an allergenic species. Mur et al. (2001) observed that the exposure to linden pollen can induce IgE-mediated rhinoconjunctivitis and cough. Fortunately, it is an entomophilous species, hence with low pollen dispersal in the air. The guidelines for designing urban green spaces with low allergy impact suggest planting *Tilia* species in areas further away from thoroughfares, homes and offices (Cariñanos and Casares-Porcel, 2011). In Florence *T. × europaea* is commonly used for urban vegetation in public parks and along the main streets of the city, in fact, more than 10% of trees managed by the municipality belongs to this species. As regard to *T. × europaea* phenology in Europe, leaf buds start to swell in April and trees generally flower in June (Pigott, 1991).

Since air temperature in an urban environment is affected by urban morphology (Petralli et al., 2013), a second aim of this study was to investigate the relationship between flowering dates and the distance from the city center and the degree of urbanization

surrounding the monitoring site in order to explore the possibility of estimating the start and the end of flowering using urban planning indicators.

Methods

Study area

A total of 60 *T. × europaea* trees, randomly selected from 6 observation sites located along an approximate east-west axis in the city centre and suburbs of Florence (Fig. 1) were observed in spring 2012. The city lies on a plain to the southwest of the Apennine mountains in the central part of Italy (Lat: 43.77N; Long: 11.26E; elevation 50 m a.s.l.) and is characterized by a sub-Mediterranean climate with a hot, dry summer, quite a wet winter, and a wet autumn and spring.

The observation sites were selected in close vicinity of the air temperature and relative humidity sensors (HOBO® PRO series Temp/RH Data Logger, Onset Computer Corporation, Pocasset, MA, USA; with naturally ventilated solar radiation shield – RS1-HOBO® PRO) that belongs to a network of sensors that have been installed in the city of Florence since 2005 (Petralli et al., 2011). All sites have an elevation of approximately 50 m a.s.l. and are located on the plain. Each observation site was selected as close as possible to the air temperature sensors location, and exposed to similar conditions in order to minimize the differences in seasonal temperature means for those trees which were not very close to their temperature sensor. The maximum distance between the trees and the sites where the sensors were located was 250 m. Air temperature data were recorded automatically at 15-min intervals, and then aggregated into hourly and daily averages for data analysis.

Vector data layers of buildings and streets of the Florence Municipality geographic information system (SIT) were used to evaluate the level of urbanization of a 250 m buffer area surrounding each observation site (Fig. 1). The following urban planning indicators were used (Petralli et al., 2013):

- percentage of impervious surfaces (IS) defined as the proportion of the buffer area covered by building or paved streets and squares (%);
- building volume density (BVD) defined as the total volume of buildings divided by the buffer area (m³/m²).

Phenological observations

At each observation site, 10 *T. × europaea* trees were randomly selected for observation, making a total number of 60 *T. × europaea* trees observed. All the trees selected were around 10–15 m high, with a 50-cm diameter at 1.3 m above ground level, and were not pruned. Each observation site was visited at least once every two days from May to June 2012 and phenological observations of the flowering stage of each tree were recorded. Three branches were selected in the lower part of the crown of each tree, and for each branch the development stage of ten inflorescences was recorded according to the following scale (Fig. 2):

- (0) no individual flower opened;
- (1) up to half of the individual flowers opened;
- (2) more than half of the individual flowers opened;
- (3) up to half of the individual flowers fallen or dry;
- (4) almost all individual flowers fallen or dry.

At every observation, a value between 0 and 4 was assigned to each inflorescence according to the corresponding phenological phase observed. Following, the sum of the inflorescence scores



Fig. 1. Map of the city of Florence (Italy) with the indication of the observation sites (from 1 to 6). The white circles corresponds to the area of 250 m radius near the observation sites centered on the air temperature sensor.

of the three branches of each tree were added together to obtain a flower development score, ranging from 0 (no individual flower opened in any one inflorescence) to 120 (almost all individual flowers fallen or dry in all inflorescences).

The start of flowering (SF) and end of flowering (EF) dates were calculated as means of 10 trees, by using a flowering index score (FI). At each site, phenophase SF and EF were identified according to the extended BBCH-scale (BBCH = Biologische Bundesanstalt, BUNDessortenamt und Chemische Industrie) proposed by Hack et al. (1992). According to this scale SF was identified by FI=6, corresponding to an average of 10% open flowers (BBCH code 61) and EF by FI=120 corresponding to “all flowers fallen or dry and fruit set visible” (BBCH code 69). Data were then interpolated to obtain the exact values of observed SF₀ and EF₀, as shown in a previous study performed in Italy (Cesaraccio et al., 2004). In particular SF₀ (i.e. the date when SF reached the threshold FI=6) was determined by linear interpolation calculated between the two consecutive observed

days in which FI was lower (1st observation) and then higher (2nd observation) than the threshold. EF₀ was calculated as the first day in which FI=120 was observed. All dates were expressed as progressive numbers starting from 1st January 2012.

For each sensor, winter and spring average air temperatures were calculated and the relationships with SF, EF were investigated by means of linear regression ($N=6$).

The relationships between SF, EF and the distance from the city center (D), the percentage of impervious surfaces (IS), the building volume density (BVD), the winter (DJF) and the spring (MAM) temperatures were also investigated by means of Pearson product moment correlation and simple linear regression ($N=6$). Linear regression coefficients and 95% confidence interval values were calculated for IS, DJF, MAM fit on observed phenological data (SF₀, EF₀) by the least square method.

Finally, smoothed maps of start and end of flowering of *T. × europaea* in 2012 were produced applying the resulting

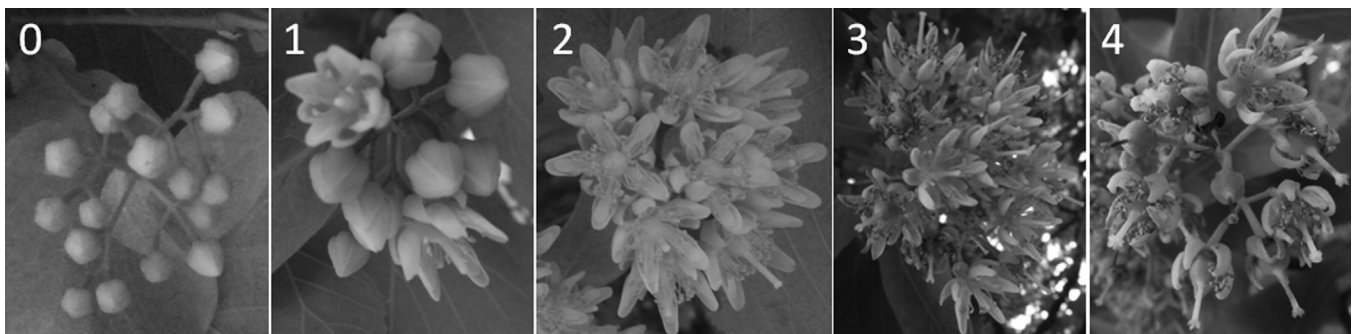


Fig. 2. Examples of each phenological phase observed (0 = no individual flower opened; 1 = up to half individual flowers opened; 2 = more than half individual flowers opened; 3 = up to half individual flowers fallen or dry; 4 = almost all individual flowers fallen or dry).

Table 1

Distance from the city centre (D), percentage of impervious surfaces (IS), building volume density (BVD) within a circle of 250 m centered on each site of observation, mean seasonal temperature: winter (DJF), spring 2012 (MAM) for each site and observed start (SF) and end (EF) flowering day expressed as progressive numbers starting from 1st January 2012, duration of flowering season in days (DUR) for each observation site and mean (μ) and standard deviation (σ).

Site	D (km)	IS (%)	BVD (m ³ /m ²)	DJF (°C)	MAM (°C)	SF (day)	EF (day)	DUR (days)
1	5.9	65.0	1.96	5.9	15.0	149.0	167.0	18.0
2	4.7	72.0	2.29	6.3	15.2	147.0	163.0	16.0
3	3.4	23.0	0.57	5.4	14.2	154.0	171.0	17.0
4	1.7	55.0	6.05	6.1	14.6	150.0	167.0	17.0
5	3.3	41.0	0.83	5.6	14.5	152.0	168.0	16.0
6	4.3	27.0	1.10	5.3	14.0	154.0	171.0	17.0
Mean (μ)	3.9	47.2	2.13	5.8	14.6	151.0	167.0	16.8
Standard deviation (σ)	1.4	20.1	2.03	0.4	0.5	2.8	3.0	0.8

Table 2

Correlation between start of flowering (SF), end of flowering (EF), impervious surface (IS%), distance from the city center (D), building volume density (BVD), winter temperature (DJF) and spring temperature (MAM) (* significance level $p < 0.05$, ** significant level $p < 0.01$, *** significant level $p < 0.001$).

Variable (Unit)	SF (day)	EF (day)	DJF (°C)	MAM (°C)
D (km)	−0.287	−0.190	0.083	0.414
IS (%)	−0.991***	−0.939**	0.955**	0.969**
DJF (°C)	−0.977***	−0.967**	–	–
MAM (°C)	−0.975***	−0.938**	–	–
BVD (m ³ /m ²)	−0.464	−0.400	0.588	0.294

equations to IS calculated on a 250 m × 250 m grid in the city of Florence and using QGIS Dufour 2.0.1.

Results

The urban characteristics and mean seasonal temperature for each site are illustrated in Table 1.

The distances from the city center varied between 1.7 km and 5.9 km, the percentage of impervious surfaces (IS) varied between 23% and 72% and BVD varied between 0.83 m³/m² and 6.05 m³/m². Winter temperatures varied between 5.3 °C (site 6) and 6.3 °C (site 2), and spring temperatures varied between 14.0 °C (site 6) and 15.2 °C (site 2). Site 6 was the coolest area and site 2 the warmest area during the entire period. (Table 1).

The dates and duration of the flowering season observed are illustrated in Table 1. The earliest start and end of flowering dates were observed at site 2 on day 147 (26 May) and day 163 (11 June) while the latest dates were observed at sites 3 and 6 on day 154 (2 June) and day 171 (19 June). Average flowering stage duration was 16.8 days, but taking into account the whole Florentine area, the flowering season in 2012 lasted 24 days (from day 147 to day 171).

Both SF and EF were significantly correlated with IS as well as with winter and spring mean temperatures (Table 2): SF was highly correlated with IS ($R = -0.991$), DJF ($R = -0.977$) and MAM ($R = -0.975$) and EF was highly correlated with IS ($R = -0.939$), DJF ($R = -0.967$) and MAM ($R = -0.938$). Winter as well as spring mean temperatures were also significantly correlated to IS ($R = -0.955$

and -0.969 , respectively, Table 2). No significant relationship was found between phenological phases (SF, EF) and the distance from the city centre nor the building volume density.

Coefficients of simple linear regression between SF, EF and IS, DJF and MAM were calculated (Fig. 3) and are presented in Table 3. A 10% increase of impervious surface significantly advanced both SF and EF by 1.4 days (Table 3). An increase in mean winter temperature significantly advanced SF by 7.0 days/°C and EF by 7.3 days/°C (Table 3). Also warmer mean spring temperature significantly advanced both SF by 6.0 days/°C and EF by 6.1 days/°C (Table 3).

The three β coefficients express the phenological response, respectively, to the impervious surface gradient (IS) and seasonal thermal variations (DJF, MAM). Since both SF and EF were significantly correlated with IS, a potential application of this type of analysis is the production of an urban phenological map that can give an estimate of *T. × europaea* flowering timing variations for the city of Florence in 2012. According to the SF map obtained by applying the linear regression established in Table 3 with IS, *T. × europaea* started flowering in the most urbanized part of Florence (day 147 in the city centre) eleven days before the greenest ones (day 158) (Fig. 4).

Discussion

Phenological data collected in spring 2012 in Florence were used to investigate the relationship between *T. × europaea* flowering,

Table 3

Estimate and 95% confidence interval of the regression coefficient (β) and the intercept (C) of the simple linear regression equations (Fig. 3) based on impervious surface (IS), winter (DJF) and spring temperature (MAM) and, respectively, fit on start of flowering (SF) and end of flowering (EF) observed in Florence in 2012 (* significance level $p < 0.05$, ** significant level $p < 0.01$, *** significant level $p < 0.001$).

Variable (unit)	Coefficient	SF (day)	EF (day)
1) IS (%)	β (day vs 10% IS)	−1.4 (−1.7; −1.1)***	−1.4 (−2.1; −0.7)**
	C (Intercept in day)	157.6 (156.2; 158.9)***	174.4 (170.8; 178.0)***
2) DJF (°C)	β (day vs temperature)	−7.0 (−9.1; −4.9)***	−7.3 (−10.0; −4.6)**
	C (Intercept in day)	191.3 (179.1; 203.6)***	210.1 (194.5; 225.7)***
3) MAM (°C)	β (day vs temperature)	−6.0 (−7.9; −4.1)***	−6.1 (−9.2; −3.0)**
	C (Intercept in day)	238.5 (210.8; 266.3)***	257.0 (211.2; 302.8)***

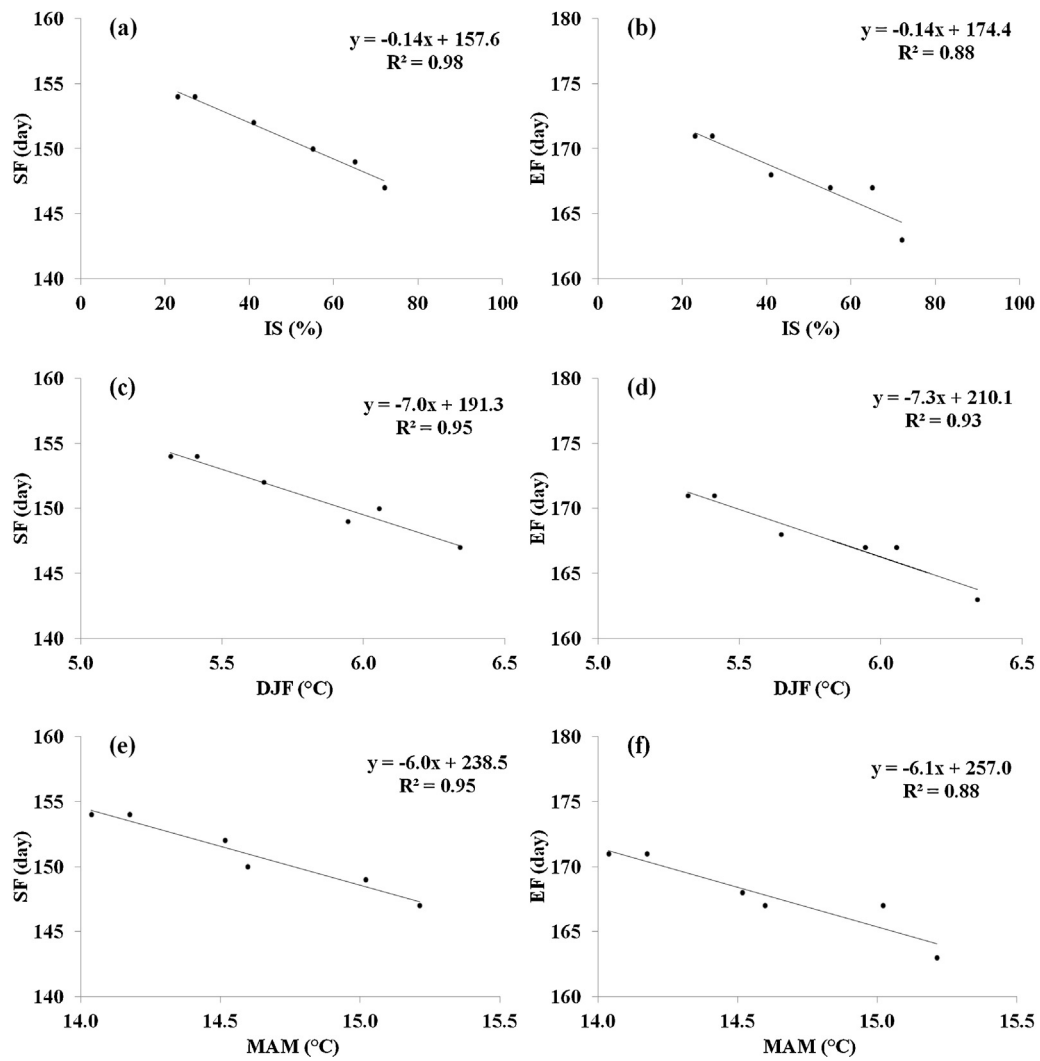


Fig. 3. Scatter plot, regression line, and equation fit of (a) SF and IS, (b) EF and IS, (c) SF and DJF, (d) EF and DJF, (e) SF and MAM, (f) EF and MAM.

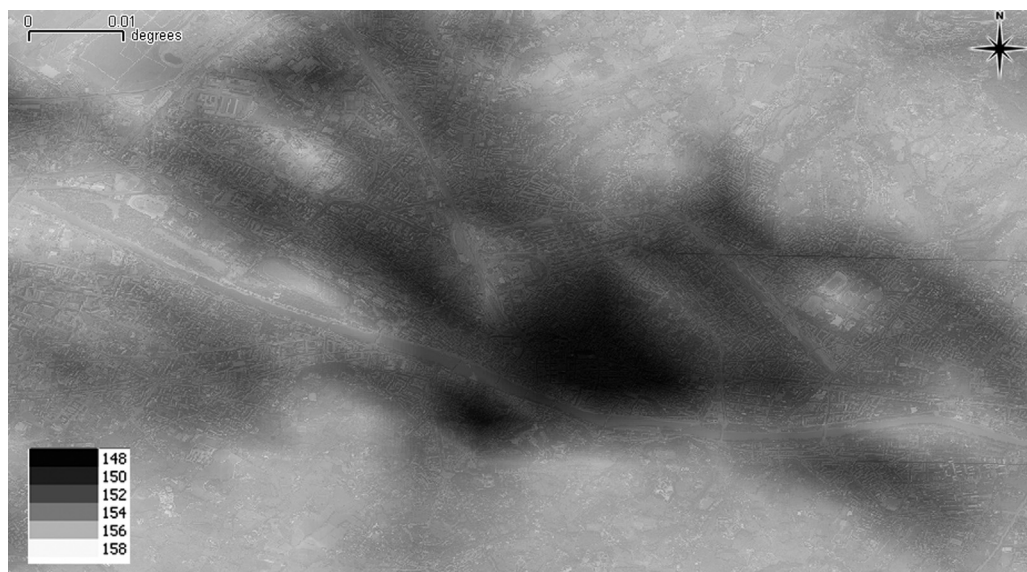


Fig. 4. Smoothed map of start of flowering (SF) in Florence in 2012 estimated by simple linear regression of the proportion of impervious surface in a 250 m × 250 m grid. SF date is expressed in a gray scale from black (day 148) to white (day 158).

seasonal temperature variations and urban surface parameters and explore a potential application of the relationship between urbanization and flowering phenology. The main findings of this study can be summarized as follows:

- (1) *T. × europaea* flowering dates showed a strong variability within the city of Florence.
- (2) Start and end of flowering were advanced by approximately 7 days for 1 °C increase in winter mean temperature and by 6 days for 1 °C increase in spring mean temperature.
- (3) The relationship between the percentage of impervious surfaces and both SF and EF was highly significant and a 10% increase of IS corresponded to an advance of 1.4 days in both phenophases.
- (4) No significant relationship was found between the start or end of flowering, the distance from the city center or the building volume density.

Even if *Tilia* species are widely used in urban environment, only few studies focused on *Tilia* genus phenology. In a study about the phenology of four *Tilia* species in the city of Lublin (Poland), the flowering season of *T. × europaea* was averagely 16 days (Weryszko-Chmielewska and Sadowska, 2010). The flowering season length observed in Lublin and in Florence was similar (16 vs. 16.8 days): even though the start of the flowering season was later by two weeks in Lublin than in Florence due to cooler spring temperatures. According to our results (Table 1), the seasonal average difference between the coolest and the hottest station is around 1 °C (1 °C in winter and 1.2 °C in spring) and the start and the end of flowering at the hottest site happen, respectively, 7 days and 8 days earlier than at the coolest one. These results are in line with studies that found a strong influence of temperature on several plant species (Estrella et al., 2007; Clark and Thompson, 2010). In Germany, an extensive study on the phenology of 78 agricultural and horticultural species over a period of more than 50 years, estimated that a mean temperature difference of 1 °C in spring was estimated to advance plant phenology by almost 4 days (Estrella et al., 2007).

The increasing size of cities and the intensive land use change from green surfaces to impervious surfaces and buildings cause thermal difference between cities and the surrounding countryside (Urban Heat Island Effect), as well as between areas of the city characterized by different levels of urbanization (Petralli et al., 2011; Petralli et al., 2013). The thermal variability induced by urbanization can consequently affect plant development and phenology.

This study showed that impervious surfaces contribute to flowering date shifts among different part of the cities ($R^2_{SF}=0.982$; $R^2_{EF}=0.881$), and a variation of impervious surface between 23% and 72% among observation sites corresponds to a difference in SF and EF of 7 and 8 days, respectively. In Florence, IS varies between 78% and 0.04% and if the linear relationship is considered valid for almost the whole range of IS, we can assume an advance of 10.9 days of the most built-up area (IS = 78%) with respect to the greenest area (IS = 0.04%) in Florence. Many researchers have investigated the differences in phenological response between rural and urban areas, and evidence of an advance in the phenological phases has been found in urban areas (Neil and Wu, 2006; Mimet et al., 2009; Shustack et al., 2009). Only a few studies have investigated the relationship between phenology and the degree of urbanization: Shustack et al. (2009) found evidences of shifts in *Lonicera maackii* (Amur honeysuckle), an invasive exotic species, along the urbanization gradient. Jochner et al. (2012) investigated the role of elevation and urbanization in the shift of flowering phases of nine tree species, and an advance of 2.6–7.6 days was observed between an entirely rural area and an entirely urban one in five of these species in flowering dates according to urbanization (Jochner

et al., 2012). It must be noted that the urban index they used was calculated on land use at a 2 km scale while our IS was calculated with a finer resolution (250 m).

No significant relationship was found between the start and the end of flowering and the distance from the city center. This result is seemingly in contrast with studies conducted in the United States (Zhang et al., 2004), where an increase in dormancy was found in relation to distance from the urban perimeter. This could be due to the shape of Florence urban area that is not compact, hence the boundaries of the urban area are not at the same distance from the city centre in all directions and built-up areas are spread discontinuously.

The relationship with IS suggests that the start and end of flowering dates are influenced more by local degree of urbanization than by the distance from the city centre alone. Our results support the hypothesis by Jochner et al. (2012), according to whom land use information could be more appropriate to define an area as urban, rather than distance from the city centre for cities that do not have a compact shape. The influence of BVD was also tested but no relationship was found neither with phenology nor with winter and spring temperature. This result is in contrast with other studies on the relationship between city morphology and air temperature distribution within the urban environment (Oke, 1988; Lindberg, 2007), suggesting that BVD might not be the most appropriate index to show the influence of urban morphology on local urban temperatures and on plant phenology. In future studies it will be interesting to analyze the influence of other urban vertical morphology indicators (street aspect ratios (H/W) for example).

In this study we also found a strong relationship between SF, EF and the temperature means at the seasonal scale (DJF and MAM). However, this relationship cannot be effectively used in cold regions where frost events are more frequent. In this case a phenological model, like a degree day model, is needed.

Conclusions and perspectives

Our findings suggest that the density of built-up surfaces can be used to estimate flowering of *T. × europaea* at the scale of a city. This can have important application in many research and management activities that concern phenology and development of plants, like for instance biometeorology, aerobiology, urban forestry and urban planning. Moreover, results can be easily presented in maps that are more familiar and easy to interpret by city managers and urban planners (Fig. 4). By now city managers and urban planners can take advantage of geographical information systems that provide detailed information about volume occupied by buildings, area occupied by streets and squares as well as location and other detailed information about green areas. Our preliminary results suggest that these informations, along with temperature records, can be used to provide an estimation of plant phenology variability at a detailed spatial scale inside the urban environment. In fact, the number of temperature sensors required to monitor an urban area can be very high and depends on city size. Furthermore the choice of the most suitable place for sensor siting could not always be allowed in a public space, like in the historical part of Florence. All these limitations can be overcome with the use of indicators based on urban spatial structure and temperature measurements at a rural site that could be used to suppress the urban thermal signal. This way temperature data collected in the rural site could provide the base temperature signal. The urban indicator could then be used to quantify the temperature signal modification, and consequently estimate phenological timing variation within the urban environment. Urban sensors could then be used to back-up and validate the results of the prediction model. Nevertheless further investigations are required to reach this goal. Indeed our study is based only

on one year of observations at six sites, therefore we need to collect new measurements and observations to support our findings as well as to validate the relationship between urbanization and phenology. However our preliminary results seem quite promising and suggest to carry on further investigation both on *T. × europaea* and other plant species used in urban forestry, especially allergenic species. This study could be a first step in the evaluation of phenological variability in the urban environment and, in perspective, its application to other plant species could lead to more integrated assessments of urban green areas.

In conclusion, our results suggest a potential application of urban morphology indicators to predict phenological shifts in an urban environment. This information can be processed using GIS to produce useful phenological maps of an existing urban area as well as to future urban planning scenarios. These informations can be integrated with other indicators to assess the seasonal benefits and drawbacks of trees in the urban landscape.

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References

- Brett, B.A., 2003. Physical environmental modeling, visualization and query for supporting landscape planning decisions. *Landscape Urban Plann.* 65, 237–259, [http://dx.doi.org/10.1016/S0169-2046\(03\)00059-8](http://dx.doi.org/10.1016/S0169-2046(03)00059-8).
- Cariñanos, P., Casares-Porcel, M., 2011. Urban green zones and related pollen allergy: a review. Some guidelines for designing spaces with low allergy impact. *Landscape Urban Plann.* 101, 205–214, <http://dx.doi.org/10.1016/j.landurbplan.2011.03.006>.
- Cecchi, L., D'Amato, G., Ayres, J.G., Galan, C., Forastiere, F., Forsberg, B., Annesi-Maesano, I., 2010. Projections of the effects of climate change on allergic asthma: the contribution of aerobiology. *Allergy* 65 (9), 1073–1081, <http://dx.doi.org/10.1111/j.1398-9995.2010.02423.x>.
- Cesaraccio, C., Spano, D., Snyder, R.L., Duce, P., 2004. Chilling and forcing model to predict bud-burst of crop and forest species. *Agric. For. Meteorol.* 126, 1–13, <http://dx.doi.org/10.1016/j.agrformet.2004.03.002>.
- Clark, R.M., Thompson, R., 2010. Predicting the impact of global warming on the timing of spring flowering. *Int. J. Climatol.* 30, 1599–1613, <http://dx.doi.org/10.1002/joc.2004>.
- Estrella, N., Sparks, T.H., Menzel, A., 2007. Trends and temperature response in the phenology of crops in Germany. *Global Change Biol.* 13 (8), 1737–1747, <http://dx.doi.org/10.1111/j.1365-2486.2007.01374.x>.
- Gill, S.E., Handley, J.F., Ennos, A.R., Pauleit, S., Theuray, N., Lindley, S.J., 2008. Characterising the urban environment of UK cities and towns: a template for landscape planning. *Landscape Urban Plann.* 87 (3), 210–222, <http://dx.doi.org/10.1016/j.landurbplan.2008.06.008>.
- Hack, H., Bleiholder, H., Buhr, L., Meier, U., Schenck-Fricke, U., Stauss, R., Witzinger, A., 1992. Einheitliche Codierung der phänologischen Entwicklungsstadien mono- und dikotyler Pflanzen. – Erweiterte BBCH-Skala, Allgemein-Nachrichtenbl. Deut. Pflanzenschutz. 44 (12), 265–270.
- Hunter, M.R., 2011. Impact of ecological disturbance on awareness of urban nature and sense of environmental stewardship in residential neighborhoods. *Landscape Urban Plann.* 101 (2), 131–138, <http://dx.doi.org/10.1016/j.landurbplan.2011.02.005>.
- Jochner, S.C., Sparks, T.H., Estrella, N., Menzel, A., 2012. The influence of altitude and urbanisation on trends and mean dates in phenology (1980–2009). *Int. J. Biometeorol.* 56 (2), 387–394, <http://dx.doi.org/10.1007/s00484-011-0444-3>.
- Lindberg, F., 2007. Modelling the urban climate using a local governmental geodatabase. *Meteorol. Appl.* 14 (3), 263–273, <http://dx.doi.org/10.1002/met.29>.
- Luo, Z.K., Sun, O.J., Ge, Q.S., Xu, W.T., Zheng, J.Y., 2007. Phenological responses of plants to climate change in an urban environment. *Ecol. Res.* 22, 507–514, <http://dx.doi.org/10.1007/s11284-006-0044-6>.
- McPherson, E.G., Simpson, J.R., Xiao, Q., Wu, C., 2011. Million trees Los Angeles canopy cover and benefit assessment. *Landscape Urban Plann.* 99, 40–50.
- Menzel, A., Sparks, T.H., Estrella, N., Koch, E., Aasa, A., Ahas, R., Züst, A., 2006. European phenological response to climate change matches the warming pattern. *Global Change Biol.* 12 (10), 1969–1976, <http://dx.doi.org/10.1111/j.1365-2486.2006.01193.x>.
- Mimet, A., Pellissier, V., Quénel, H., Aguejedad, R., Dubreuil, V., Rozé, F., 2009. Urbanisation induces early flowering: evidence from *Platanus acerifolia* and *Prunus cerasus*. *Int. J. Biometeorol.* 53, 287–298, <http://dx.doi.org/10.1007/s00484-009-0214-7>.
- Mubareka, S., Koomen, E., Estreguil, C., Laval, C., 2011. Development of a composite index of urban compactness for land use modeling applications. *Landscape Urban Plann.* 103, 303–317, <http://dx.doi.org/10.1016/j.landurbplan.2011.08.012>.
- Mur, P., FeoBrito, F., Lombardero, M., Barber, D., Galindo, P.A., Gomez, E., Borja, J., 2001. Allergy to linden pollen (*Tilia cordata*). *Allergy* 56, 457–458.
- Neil, K., Wu, J., 2006. Effects of urbanization on plant flowering phenology: a review. *Urban Ecosyst.* 9 (3), 243–257, <http://dx.doi.org/10.1007/s11252-006-9354-2>.
- Neil, K.L., Landrum, L., Wu, J., 2010. Effects of urbanization on flowering phenology in the metropolitan phoenix region of USA: findings from herbarium records. *J. Arid Environ.* 74, 440–444, <http://dx.doi.org/10.1016/j.jaridenv.2009.10.010>.
- Nowak, D.J., Greenfield, E.J., 2012. Tree and impervious cover changes in the United States. *Landscape Urban Plann.* 107, 21–30, <http://dx.doi.org/10.1016/j.landurbplan.2012.04.005>.
- Ohashi, Y., Kawakami, H., Shigeta, Y., Ikeda, H., Yamamoto, N., 2012. The phenology of cherry blossom (*Prunus yedoensis* “Somei-yoshino”) and the geographic features contributing to its flowering. *Int. J. Biometeorol.* 56 (5), 903–914, <http://dx.doi.org/10.1007/s00484-011-0496-4>.
- Oke, T.R., 1987. Boundary Layer Climates. Published by Methuen & Co Ltd. British Library Cataloguing in Publication Data, Great Britain (Printed in Great Britain).
- Oke, T.R., 1988. The urban energy balance. In: *Progress in Physical Geography* December 12., pp. 471–508, <http://dx.doi.org/10.1177/030913338801200401>.
- Parmesan, C., Yohe, G., 2002. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421, 37–42, <http://dx.doi.org/10.1038/nature01286>.
- Petralli, M., Massetti, L., Orlandini, S., 2011. Five years of thermal intra-urban monitoring in Florence (Italy) and application of climatological indices. *Theor. Appl. Climatol.* 104 (3/4), 349–356, <http://dx.doi.org/10.1007/s00704-010-0349-9>.
- Petralli, M., Massetti, L., Brandani, G., Orlandini, S., 2013. Urban planning indicators: useful tools to measure the effect of urbanization and vegetation on summer air temperatures. *Int. J. Climatol.*, <http://dx.doi.org/10.1002/joc.3760>.
- Pigott, C.D., 1991. Biological flora of the British Isles. No. 174. *Tilia cordata* Miller. *J. Ecol.* 79, 1147–1207.
- RCEP, Royal Commission On Environmental Pollution, 2007. The Urban Environment. RCEP, Royal Commission On Environmental Pollution, Norwich, pp. 83 <http://webarchive.nationalarchives.gov.uk/20080110004515/http://www.rcep.org.uk/urban/report/urban-environment.pdf> (TSO).
- Roy, S., Byrne, J., Pickering, C., 2012. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. *Urban For. Urban Greening* 11 (4), 351–363, <http://dx.doi.org/10.1016/j.ufug.2012.06.006>.
- Schleip, C., Sparks, T.H., Estrella, N., Menzel, A., 2009. Spatial variation in onset dates and trends in phenology across Europe. *Clim. Res.* 39 (3), 249–260, <http://dx.doi.org/10.3354/cr00830>.
- Shochat, E., Warren, P.S., Faeth, S.H., 2006. Future directions in urban ecology. *Trends Ecol. Evol.* 21 (12), 661–662, <http://dx.doi.org/10.1016/j.tree.2006.09.006>.
- Shustack, D.P., Rodewald, A.D., Waite, T.A., 2009. Springtime in the city: exotic shrubs promote earlier greenup in urban forests. *Biol. Invasions* 11, 1357–1371, <http://dx.doi.org/10.1007/s10530-008-9343-x>.
- Syers, D.M., Chappellka, A.H., Marzen, L.J., Somers, G.L., 2010. Developing a land-cover classification to select indicators of forest ecosystem health in a rapidly urbanizing landscape. *Landscape Urban Plann.* 94, 158–165, <http://dx.doi.org/10.1016/j.landurbplan.2009.09.006>.
- Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kaźmierczak, A., Niemela, J., James, P., 2007. Promoting ecosystem and human health in urban areas using Green Infrastructure: a literature review. *Landscape Urban Plann.* 81 (3), 167–178, <http://dx.doi.org/10.1016/j.landurbplan.2007.02.001>.
- United Nations, Department of Economic and Social Affairs, Population Division, 2012. World Urbanization Prospects, the 2011 Revision. United Nations, Department of Economic and Social Affairs, Population Division, New York, NY (Press release).
- Van de Voorde, T., Jacquet, W., Canters, F., 2011. Mapping form and function in urban areas: an approach based on urban metrics and continuous impervious surface data. *Landscape Urban Plann.* 102, 143–155, <http://dx.doi.org/10.1016/j.landurbplan.2011.03.017>.
- Werysko-Chmielewska, E., Sadowska, D.A., 2010. The phenology of flowering and pollen release in four species of linden (*Tilia* L.). *J. Apic. Sci.* 54 (2), 99–108.
- Wielgolaski, F.E., 2001. Phenological modifications in plants by various edaphic factors. *Int. J. Biometeorol.* 45 (4), 196–202, <http://dx.doi.org/10.1007/s004840100100>.
- Zhang, X., Friedl, M.A., Schaaf, C.B., Strahler, A.H., Schneider, A., 2004. The footprint of urban climates on vegetation phenology. *Geophys. Res. Lett.* 31 (L12209), <http://dx.doi.org/10.1029/2004GL020137>.
- Ziska, L.H., Gebhard, D.E., Frenz, D.A., Faulkner, S., Singer, B.D., Straka, J.G., 2003. Cities as harbingers of climate change: common ragweed, urbanization, and public health. *J. Allergy Clin. Immunol.* 111, 290–295, <http://dx.doi.org/10.1067/mai.2003.53>.