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Review

Urban phenological studies – Past, present, future

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ABSTRACT

Phenology is believed to be a suitable bio-indicator to track climate change. Based on the strong statistical association between phenology and temperature phenological observations provide an inexpensive means for the temporal and spatial analysis of the urban heat island. However, other environmental factors might also weaken this relationship. In addition, the investigation of urban phenology allows an estimation of future phenology from current information since cities with their amplified temperatures may serve as a proxy for future conditions. Nevertheless, the design of spatial compared to long-term studies might be influenced by different factors which should be taken into consideration when interpreting results from a specific study. In general, plants located in urban areas tend to flush and bloom earlier than in the countryside. What are the consequences of these urban–rural differences? This review will document existing findings on urban phenology and will highlight areas in which further research is needed.

1. Introduction

One of the most central problems the world is currently facing is anthropogenic climate change. During the period 1880–2012 mean global air temperature increased by 0.85 [0.65 to 1.06] °C which is very likely attributable to the increase in anthropogenic greenhouse gases, with carbon dioxide (CO_2) being the most important driver (IPCC, 2013). Although global temperature change has been rather flat for the last decade (Hansen et al., 2013), temperature will – depending on the underlying scenario – increase between 1.0 and 3.7 [0.3 to 4.8] °C by the end of the 21st century (IPCC, 2013).

Implications of global climate change, particularly related to the increase in air temperature, can already be seen in various biological systems (Parmesan and Yohe, 2003; Root et al., 2003; Rosenzweig et al., 2008; IPCC, 2013). One of the best bio-indicators of climate change is phenology (Walther et al., 2002; Badeck et al., 2004; Cleland et al., 2007), the timing of natural recurring events such as leaf unfolding, flowering, fruit ripening or leaf colouring and fall. The strong relationship between spring phenology and air temperature in temperate regions allows observed changes in phenology to be related to changes in temperature (Sparks and Carey, 1995; Menzel, 1997; Menzel and Fabian, 1999; Menzel et al., 2006).

Human activities do not only modify climatic conditions at the global scale by altering the composition of atmospheric gases; they are also involved in a much more localised phenomenon – the urban heat island (UHI) effect that is associated with higher temperatures in cities (Landsberg, 1981; Fezer, 1995; Matzarakis, 2001). This temperature increase is caused by the replacement of natural landscapes with impermeable surfaces and built up areas. Unlike natural environments, urban areas are mostly characterised by highly compacted or impermeable surfaces with distinctive differences in heat capacity and conductivity (Landsberg, 1981). The relatively low abundance of vegetation implies less evapotranspiration and therefore higher temperatures (Oke, 1976; Landsberg, 1981). In addition to the common perception that the reduction in evaporative cooling is mainly responsible for the UHI effect (Taha, 1997), it was recently found that the efficiency of heat convection to the lower atmosphere, which depends on the local background climate, is also of major importance (Zhao et al., 2014). The emission of sensible heat along with latent heat and chemical generation of moisture associated with private and industrial energy consumption are additional factors contributing to increased urban temperatures (Sailor, 2011). Urban air pollutants have an effect on energy fluxes: particulate matter absorbs/scatters the incoming solar radiation resulting in a decrease of global radiation

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and an increase in diffuse radiation (Landsberg, 1981; Kuttler, 2004). Absorption and re-emission by infrared active gases and aerosols within urban air lead to higher downward longwave atmospheric radiation (Kuttler, 2004).

The magnitude of the temperature difference between the city and its countryside is influenced by prevailing synoptic weather conditions (Landsberg, 1981): clear and calm nights during winter are associated with the highest excess heat. Moreover, the UHI depends on the size of the city and its building density (Landsberg, 1981; Zhang et al., 2004). The UHI effect has been well documented for numerous cities in different parts of the world (Landsberg, 1981; Bründl et al., 1987; Matzarakis, 2001) ranging on average from +0.5 to +3.0 °C with maximum values of +15 °C during specific weather conditions (Kuttler, 2004).

2. Scope of urban phenology studies

Studies on urban phenology are useful in several ways. First, they allow for the detection of urban heat islands. Second, they can be used for the assessment of climate change impacts on phenology (Fig. 1). Furthermore, urban phenology is valuable in citizen science projects since people who participate in phenological observations will learn more about ecological processes and changes while simultaneously awareness on climate change and its impacts will be strengthened (Butler and MacGregor, 2003; Gazal et al., 2008).

2.1. Detection of urban heat islands

Based on the statistical association between phenology and temperature (Cannell and Smith, 1986; Wielgolaski, 1999; Menzel and Fabian, 1999), phenological observations provide a suitable and inexpensive basis for the temporal and spatial analysis of the urban heat island (e.g., Omoto and Aono, 1990; Bernhofer, 1991; Lakatos and Gulyás, 2003; Matsumoto et al., 2009).

Phenological observations for assessing microclimatic conditions have a long tradition in temperate cities. Numerous broad-scale (i.e., spatial/local) and long-term studies exist on phenology in urban areas, especially in Europe, North America and Asia (see Table 1). Broad-scale studies are characterised by a dense coverage of a restricted region and are often based on a single or a few observation years (e.g., Mimet et al., 2009; Fukuoka and Matsumoto, 2003; Lakatos and Gulyás, 2003; Jochner et al., 2013a). Phenological observations involving citizen science (with school children, students or other volunteers) can result in a high number of observation sites and may imply a greater geographical extent (e.g., Henniges and Chmielewski, 2006; Gazal et al., 2008). Long-term studies (e.g., Rötzer and Sachweh, 1995; Defila, 1999; Rötzer et al., 2000; Jochner et al., 2012) which are mostly based on data derived from phenological networks focus on longer periods but mostly incorporate fewer observation sites where preferably always the same individual is observed. Phenological studies do not just include ground observations at the species level but also remote sensing referring to the ecosystem level (e.g., White et al., 2002; Fisher et al., 2006). In addition, herbarium data which date back several decades or centuries can be utilised to detect phenological changes in urban and rural environments (e.g., Primack et al., 2004; Lavoie and Lachance, 2006; Neil et al., 2010).

2.1.1. Urban–rural differences

A simple method to describe the effect of the UHI on phenology is the investigation of differences between the city and the countryside (Rötzer and Sachweh, 1995). In general, plants tend to develop earlier in the cities with an advance from a few days up to a couple of weeks compared to their rural surroundings (see Table 1). Zhang et al. (2004) reported that the UHI effect on plant phenology was stronger in North America than in Europe or Asia; a fact probably related to the dense and vertical urban design of North American cities causing higher urban temperatures (Zhang et al., 2004; Bonan, 2002). In addition, different species or different phenophases within the same species respond differently to urban climate. Herbaceous plants are more sensitive to microclimatic variation than trees (Mimet et al., 2009); early phases are known to be more sensitive to temperature (Fitter and Fitter, 2002) and are additionally influenced by the amplified UHI effect in winter (Rötzer and Sachweh, 1995; Defila, 1999; Rötzer et al., 2000; Jochner et al., 2012). A recent study demonstrated that first flowering dates of wind-pollinated species were associated with greater advances than insect-pollinated species (Ziello et al., 2012a). This is in contrast to the finding of Fitter and Fitter (2002) who reported greater advances for insect-pollinated plants. Both these studies, however, were not specifically based on urban–rural comparisons. Detailed investigations related to the differences in pollination types in urban areas are still lacking and further research is required to reveal likely different responses.

Unlike spring and summer phenophases, autumn phenophases are not always associated with distinct urban–rural differences: Defila (1999) reported no differences for autumn phenophases in urban and rural sites of Zurich, Switzerland. Rötzer (2007) documented a four day advance of leaf colouring of horse chestnut (*Aesculus hippocastanum*) in cities in Bavaria, Germany, which, however, might be influenced by the leafmining moth. Conversely, International Phenological Garden (IPG) data revealed that densely populated areas were linked to a delay of five days for leaf colouring and leaf fall (Rötzer, 2007). In urban areas of Japan, leaf colouring of gingko (*Gingko biloba*) and Japanese maple (*Acer palmatum*) occurred up to three weeks and ten days later, respectively (Fukuoka and Matsumoto, 2003). Rötzer (2007) suggested that less densely built areas were linked to a delay in autumn onset dates due to beneficial high temperatures; plants in extreme densely built areas, however, were susceptible to stressful environmental conditions such as increased pollution or soil water deficit and might respond by earlier leaf fall. This is also in agreement with Ziska et al. (2003) who documented earlier senescence for common ragweed (*Ambrosia artemisiifolia*) in urban Baltimore, USA. These results show that there is still a lack of knowledge how autumn phenophases in cities are influenced by environmental factors and further urban studies should include autumn phenological events.

Numerous studies using satellite/space borne remote sensing reported a prolongation of the growing season in urban areas, mostly attributable to an earlier start of the season. For example

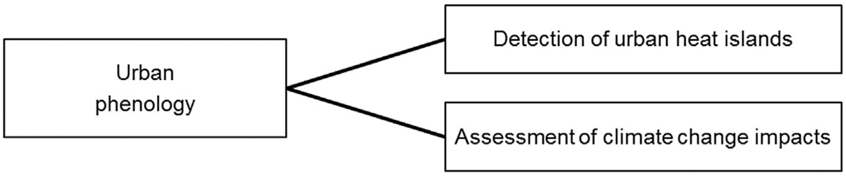

Fig. 1. Application fields of urban phenology.

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