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Collection 2, Climate change and its impacts

The impact of climate change will hit urban dwellers first – Can green infrastructure save us?

By Rüdiger Grote, 11 June 2019

RESEARCH ARTICLE

Two phenomena that can cause large numbers of premature human deaths have gained attention in the last years: heat waves and air pollution. These two effects have two things in common: They are closely related to climate change and they are particularly intense in urban areas. Urban areas are particular susceptible to these impacts because they can store lots of heat and have little opportunity for cooling off (also known as the urban heat island effect). In order to mitigate these impacts and to establish an environment that protects human health and improve well-being, implementation of green infrastructure – trees, green walls, and green roofs – is commonly proposed as a remedy. More trees, hedges and lawns are intuitively welcome by people living in cities for their beautifying effects, but to which degree can such greening actually counterbalance the expected effects of climate change? In this review I would like to investigate what science can offer to answer this question.

The threat of temperature rise to human health

Heat waves are one of the most direct climate-related threats to human health. Several reviews have demonstrated that the impacts of hot spells on human physiology reach from decreasing work efficiency [T. Kjellstrom et al., 2016] to increased mortality [S.N. Gosling et al., 2009]. In fact, the exceptional heat wave that hit most of Europe in 2003 has been estimated to cause more than 20,000 premature deaths in Italy alone [S. Hajat and T. Kosatky, 2010]. Overall, a comprehensive report from the World Health Organization estimates that every additional 1 degree Celsius (^{o}C) in a heat wave leads to a 3% or more increase in mortality [M. Ezzati et al., 2004].

Heat waves and their impacts have increased in the recent past and are expected to increase further with ongoing climate change. Figure 1 illustrates how the intensity and frequency of extreme events changes under a general warming assuming no change in the shape of probability distribution.

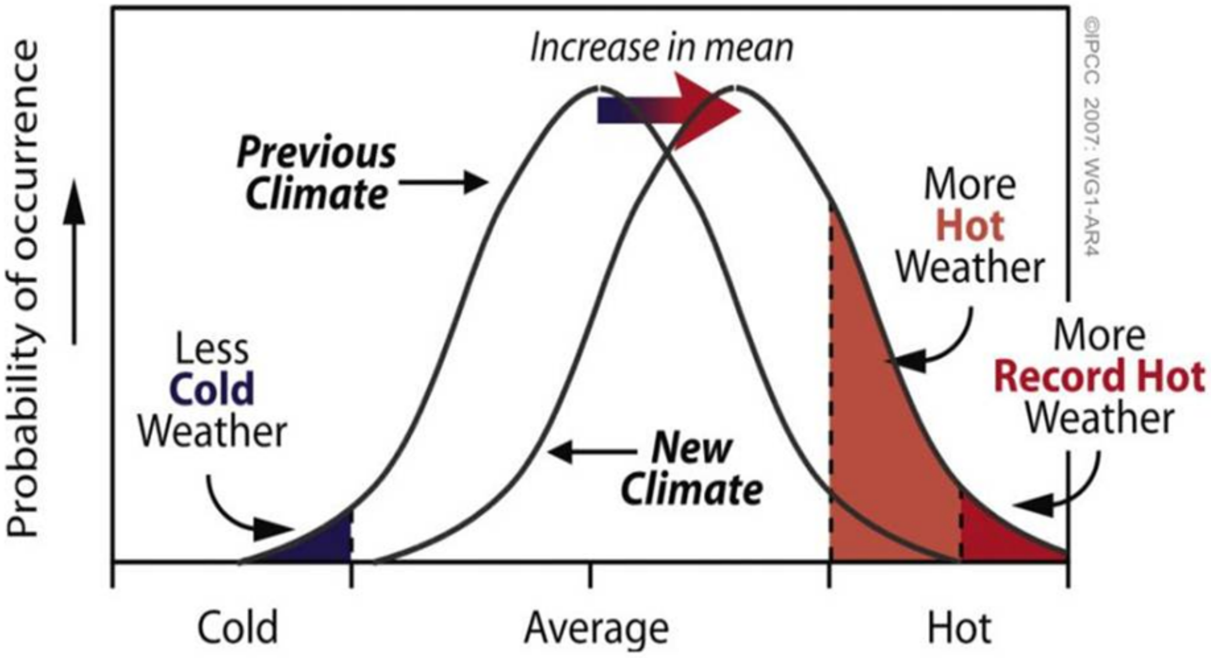

Figure 1: Scheme illustrating the disproportionate effect of global warming (i.e. an increase of mean annual temperature) on extreme and record temperatures assuming no change in general probability distribution [IPCC, 2007].

Indeed, similar patterns have been observed in the past century. For example in Sweden, mortality due to heat extremes has been doubled during the last 80 years [D. Oudin Astrom et al., 2013]. In a recent analysis it was concluded that the likeliness of a heatwave such as that from 2003 has already increased from occurring twice a century to twice a decade [N. Christidis et al., 2015].

The expectations for future developments are even worse: By the end of the 21st century, heat waves will have intensified and elongated in Europe and North America [T.C. Peterson et al., 2014] and countries in central Europe are expected to experience the same number of hot days as are currently experienced in southern Europe [M. Beniston et al., 2007]. In other words, there will be about 11 days per year more – 36 days instead of 25 days – that cross the threshold of 29 ^{o}C [H.M. Hanlon et al., 2015].

The problems arising with higher temperatures are not limited to global climate warming but also to regional and local attributes. Higher storage capacities for heat in stones and concrete together with a large amount of these materials are responsible for the hotter conditions in cities, also known as the urban heat island (UHI) effect. It is additionally fueled by the lack of water (to provide cooling) as well as reduced air movements that is accompanied with sealed surfaces and the close proximity of tall buildings [S. Grimmond, 2007]. Note that another effect of such buildings actually leads to cooling rather than heating which is the occurrence of more shade – a reason for the traditionally narrow streets in many African cities [S. Alavipanah et al., 2018]. However, since this positive effect is not dominant in Central Europe and North America, heat events in these regions are generally more intense within cities than outside. This is particular dangerous due to the coincidence of detrimental conditions on the one hand and a high density of population on the other.

And a high temperature during heat waves is not the only detrimental condition in urban areas. Health problems are particularly likely if extreme heat co-occurs with air pollution, which is unfortunately very common [M. Ezzati et al., 2004]. The key air pollutants in cities globally are fine particulate matter, ozone, nitrous oxides and sulfur dioxide [*“WMO Fact sheets / Ambient (outdoor) air quality and health”*, 2018]. In addition, so-called volatile organic compounds (VOCs), an inhomogeneous group of carbon-containing molecules with many of them having toxic effects, need to be considered.

There are various reviews of the specific effects of these substances on human health in the literature [P.M. Mannucci et al., 2015]. Particulate matter has various natural and anthropogenic sources with transport and industry emissions being the dominating ones in cities. Also, nitrous oxides and VOCs originate mostly from traffic exhaust, although the latter compounds are also emitted from solvents that are used in many industrial processes or are formed by secondary processes from gases. Sulfur dioxide is the product of burning sulfur containing fuels for households, industry or electricity production. Finally, ozone is not emitted at all but solely formed by air chemical processes, mostly requiring nitrous oxides, VOCs and radiation energy. Please note that CO_2, the most important greenhouse gas, has not been put onto this list although it is emitted in large quantities from urban regions (around 70 %) since it is not directly harmful to humans (except in very high concentrations not relevant here).

High concentrations of pollutants can originate from a high input-rate (i.e. emission or formation) and/or a low outflow rate (which is mainly determined by deposition of pollutants at various surfaces and the wind that transports the pollution away). To a certain degree, chemical reactions in the air also play a role, although for most conditions in cities this is only relevant for ozone and can be the reason for relatively low concentrations in city centers. Since heat waves are often accompanied with high emissions due to energy consumption for air conditioning as well as low air exchange rates that emanate from relatively stable weather conditions, air quality decreases during heat events.

However, this is not the whole story. As chemical reactions are sped up by higher temperature, heat also favors the formation of secondary pollutants such as ozone, worsening conditions even further [R. Vautard et al., 2007]. For example, the 2003 European heat wave led to 4-fold higher exposition of ozone (expressed as the total concentrations that exceeded 40 parts of ozone per billion of other molecules (= 80 µg m^{-3}), a concentration below which detrimental effects are not expected, also known as AOT40) compared to average summer conditions [E. Pellegrini et al., 2007]. In other words, the impact of heat and air pollution together is more than the sum of both components alone.

Since climate change is now generally accepted in political discussions, increasing impacts of heat waves on human health are also recognized as a potential threat for future urban living conditions [A. Baklanov et al., 2016]. One of the most prominent suggestions in this debate is to increase the ‘Green Infrastructure’ of cities, which includes lawns, hedgerows, urban forests and mixed structures such as gardens and parks as well as green roofs and walls. The properties and impacts of these will be the focus of the following section.

The promises of Green Infrastructure

It is well known and based on long-term experience that vegetation improves human comfort in hot environments which is due to two processes: shading and the transformation of liquid into gaseous water, a process that is termed evaporation. Plants can drag up water from deep within the soil that is otherwise not easily available for this process and channel it through their body and leaves into the air.

For example, the gardens of the Palace Generalife, which is part of the ancient Alhambra in Spain, have already been built on this knowledge in order to create a comfortable environment. Although trees were less abundant than today and the primary focus was on flowering and fruit production, the approximately 170 different and well-watered plant species also served for mitigation of high temperatures (see Figure 2). In fact, midday maximum air temperature in those gardens can be up to 10 °C less than in the exterior [B.J.

Alcala, 1999], a magnitude indicating the potentials of urban greens.

Figure 2: The gardens of the Generalife at the Alhambra in Granada, Spain build in the 13th century (Copyright: CC BY-SA 4.0, source: [“*https://commons.wikimedia.org/wiki/File:Generalife,_G%C3%A4rten_in_der_Alhambra.jpg?uselang=de*“, 2018]).

It should be noted that cooling due to evaporation depends on the availability and the usage of water. Tree species do use this resource differently, either according to their current demand or according to the available supply. Depending on which of these strategies are used, cooling might work with full intensity but only for a short time or might decrease continuously over a prolonged period [S. Gillner et al., 2017]. But even under well-watered conditions, cooling by shading as well as evaporation depends on species properties, in particular the amount of leaf area per ground area and the ability to conduct water through the system. In a recent investigation on street trees of 10 different species in Germany, these properties accounted for up to 2 °C differences in air cooling [T. Scholz et al., 2018].

How do trees and other plants that may be introduced to decrease urban peak temperatures affect air pollution levels? In fact, there is no easy answer to this. On the one hand, air pollution can be mitigated by urban greens that directly capture pollutants with their surfaces but can also be increased because they might function as a wind barrier and thus cause pollutants to have a longer residence time in the atmosphere [L.D. Emberson et al., 2013].

Plants remove pollutants from the air in two ways: Deposition on all surfaces including the large leaf area of trees and other plants, and due to uptake into the plant. The first process affects mostly particles. It depends on the size of the tree crown as well as on the amount, size and shape of leaves and is more effective in conifers than in broadleaved species [R. Grote et al., 2016]. The second process, plant uptake, that is plant uptake is particularly important for gaseous pollutants such as ozone and nitrogen oxides and depends on the strategy of plants regarding water use.

In short, plants with high water consumption that have the largest (short-term) effect on temperature are also most effective in taking up gaseous pollutants. However, one should keep in mind that these pollutants are toxic not only for humans but also for plants! Too much of it will first cause the plants to reduce their uptake capacity (by closing the openings in the leaf surface – the so-called stomata cells) and then lead to serious leaf damages and decline [F. Gao et al., 2016].

The overall effect for green infrastructure on air pollution thus depends on the species, plant size and health status, the kind and intensity of pollution, wind speed (or turbulence), and water availability. Empirical studies therefore differ in their results.

A recent study estimated the decrease of particle concentration due to urban lawns and trees in London (UK) to be up to 7-9% [A.P.R. Jeanjean et al., 2017], which was a similar effect than the one of street trees on nitrogen oxides in Pamplona (Spain) [J.-L. Santiago et al., 2017]. In contrast, gaseous traffic pollutants (i.e. nitrous oxides) were increased by 3-19% due to hedgerows planted in parallel to major streets [C. Gromke et al., 2016].

The combined effect of temperature- and pollutant-effect on health is even more difficult to estimate. However, some cases show that tree density can be in fact correlated with less asthma [I. Alcock et al., 2017] or cardio-metabolic conditions [O. Kardan et al., 2015]. Also, it has been estimated that the number of heat related deaths of elderly people during extreme events may be reduced by 50% due to green infrastructure [O. Buchin et al., 2016].

Other aspects of how trees might affect air pollution also need to be considered: For example, cooling due to increased vegetation cover also decreases the formation of ozone and other secondary pollutants solely because the photochemistry reactions are slower if temperatures are lower [J. Fallmann et al., 2016]. Another important aspect is the emission of pollen that may lead to allergenic problems [P. Cariñanos et al., 2016] and other organic substances that can be highly reactive and substantially contribute to ozone and particle formation [C. Calfapietra et al., 2013].

Since the emission of these so called BVOCs (biogenic volatile organic compounds) increases exponentially with temperature, the abundance of highly emitting tree species such as oaks, poplars or plane trees can constitute a substantial risk for air quality during heat waves [G. Churkina et al., 2017]. In addition to the occurrence of particular trees and high temperatures, the formation of ozone is also determined by the ratio between BVOCs and anthropogenic pollutants, in particular nitrogen oxides. This renders the air quality in some cities very sensitive to these emissions as for example Berlin [B. Bonn et al., 2018] while it isn't a big issue in others such as Beijing [A. Ghirardo et al., 2016].

From the analysis of impacts, it can be concluded that increasing the abundance of green infrastructure is almost always effective in decreasing summer temperatures and thus mitigating climate change effects in urban areas. The efficiency of measures may vary with the selection of species and the given climate conditions but the real concern about a higher abundance of green-infrastructure is that air pollution may worsen due to increased ozone formation or decreased air movements [P. von Döhren and D. Haase, 2015]. How can urban planning adequately be guided to optimize the overall effects?

The right balance of measures

Increasing the abundance of green infrastructure with the aim to increase human well-being has already developed into a very prominent measure. For example many of the larger cities in the US now have 'million-tree' programs, with New York City having recently established this target [*"http://www.milliontreesnyc.org/*", 2018]. The Beijing administration also has planted more than a million new trees and shrubs between 2005 and 2008 in order to improve the air quality and the general appearance of the city for the Olympic Games [A. Ghirardo et al., 2016]. These plantings are not based on – or accompanied with – scientific investigations so that location of new trees is determined by available space, and selection of species is built on convention or convenience rather than to establish the largest benefit under changed environmental conditions.

Finding an optimum solution for implementing green infrastructure is not easy because of the potentially large number of objectives (improving thermal and acoustic environment, air quality, storm water management, aesthetics, biodiversity, …), an equally large number of limitations (susceptibility to pollution including salt, drought, herbivores, …), and the need to hold down disservices and costs (emission of pollen and reactive organic substances, water consumption, destruction of infrastructure, reducing air exchange, …). A couple of rough frameworks have been proposed that try to integrate at least the majority of these targets and constraints into a decision support matrix [F.J. Escobedo et al., 2011] [D.E. Pataki et al., 2011].

However, the main problem is the lack of a common unit to better compare benefits and costs. For example the benefit of cooling is given in Celsius units while the removal of carbon dioxide and pollutants is measured in mass units such as kg. On the other hand there are planting and maintaining costs that are monetary values as well as changes in air pollutant exposition that would be reported in increases or decreases of peoples health status. So how can we give a value to every effect that is comparable to each other in order to support decision making in policies [J. Shapiro and A. Báldi, 2014]?

A method that enables comparison in terms of costs and gains is to define the ‘return of investment’ (ROI) for a specific objective. The expression is well established in economic science and describes the benefit that you get for an invested amount of money [R. McDonald et al., 2016]. This method considers that the value of an investment tends to decrease with the amount of investment.

To translate this into a green infrastructure example, ten trees don’t take up 10-fold the amount of pollutants because the uptake depends on the pollutant concentration that has already been decreased by the first tree. Therefore, the ROI can indicate the most urgently needed measure (i.e. the one that gives the highest increase in ROI per unit investment) as well as the most effective amount of investment (i.e. up to a level where the value per unit money is largest). The authors present several fascinating case studies showing that for example targeting air pollution is most urgent in Asian metropoles such as Beijing, while in less polluted cities such as Denver (US), investment in heat reduction is considerably more rewarding [R. McDonald et al., 2016].

Despite considering the multi-functionality of green spaces has been acknowledged as highly important few integrated assessment tools have yet been suggested [R. Hansen et al., 2019]. A tool to overcome the difficulties of judging different benefits of urban greens, so called ‘ecosystem services’ which has been developed since the 1990s to evaluate the value of ecosystem services is the i-Tree Eco model [F. Baró et al., 2014]. It assigns monetary values from services such as air pollution removal (dollar per kg removed) and energy savings (dollar per unit energy which has been saved due to a reduced temperature regime) that are derived from specific tree properties such as leaf area (Figure 3).

This model is relatively easy to apply and has been used particularly in the US, where the necessary environmental input data are widely accessible [E.G. McPherson et al., 2017]. Despite having been used also for city trees outside the US [M. Tallis et al., 2011], there are still problems with the approach regarding the valuation and species parameterization [R. Pace et al., 2018], the independence from people’s abundance [H. Madureira and T. Andresen, 2014], as well as some missing effects such as cultural and recreational issues [B.L. Keeler et al., 2019] or pollen emission [P. Carinanos et al., 2017].

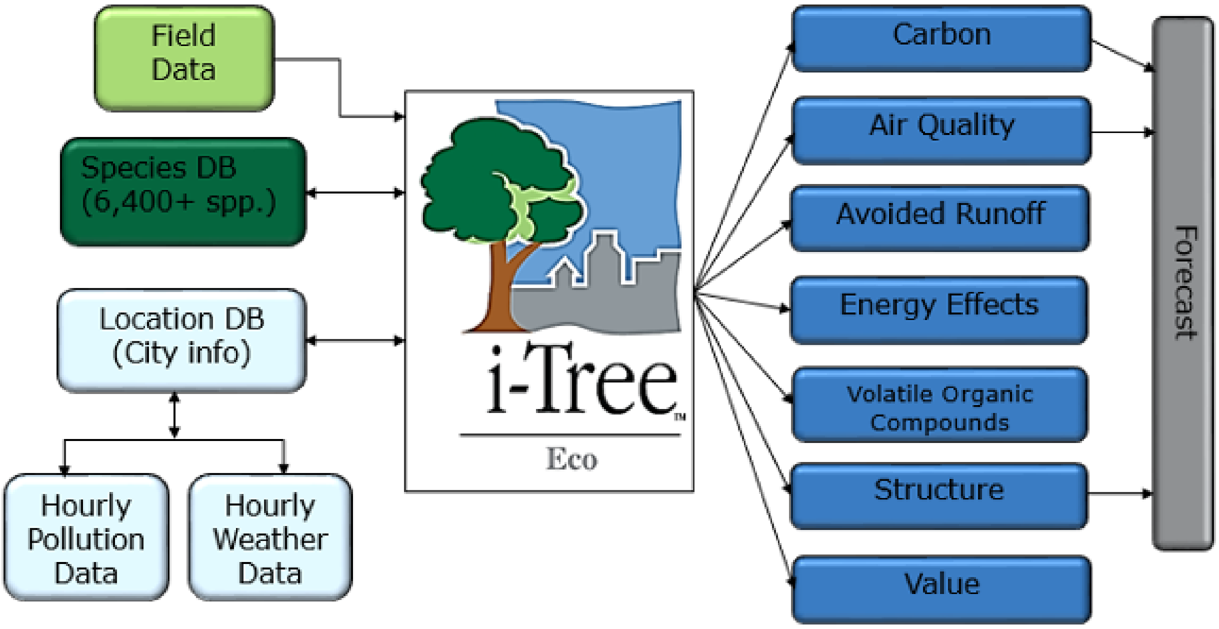

Figure 3: Tree data and model function relationships for the i-Tree Eco model (obtained from web site: [*“https://www.itreetools.org/eco/overview.php“*, 2018]).

Overall, an increased green infrastructure can certainly help reduce dangerous impacts related to climate warming in cities. However, there are some pitfalls that demand more effective decision making of where to plant which kind of green. Developing integrated models that consider various ecosystem services in a common unit such as money seems to be a promising avenue although there are still a number of obstacles to be eliminated. However, it should not be forgotten that every activity in this direction is trying to mitigate damage that should better be prevented by reductions on greenhouse gas and pollution emissions.

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