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Illustration on the front cover: Magnus Rönn

ADAPTING GREEN-BLUE ROOFS TO NORDIC CLIMATE

BRIDGET THODESEN, TORE KVANDE, HELGA THERESE TILLEY TAJET, BERIT TIME AND JARDAR LOHNE

Abstract

This paper reviews research literature on the subject of the potential role of green-blue roofs within a Nordic urban environment, to find potential implications for stormwater handling of research carried out and knowledge gaps important for future research.

The research carried out has been based on a scoping literature review using the most relevant databases and search engines. In addition, a climate adaptation mapping of the Nordic countries was worked out in order to establish key characteristics and major framework conditions specific to the region.

The research literature on green-blue solutions in general was found to be rich. It proved more limited concerning the specific conditions of green-blue roofs relevant within a Nordic urban environment. Three main functions were found to be sought after when introducing green-blue roofs, notably vegetation, insulation and water retention. Knowledge gaps were identified within all these three major areas of interest.

The limited research on the topic within a Nordic context has rendered the establishment of proper guidelines difficult. In order to address the challenges to which green-blue solutions in general and green-blue roofs in particular are thought to solve, further research is needed within areas pointed out within this paper.

Keywords:
Nordic climate, climate adaptation, green-blue roofs, stormwater, urban environment

Introduction

Researchers and planners are uniquely positioned to address the challenges brought on by climatic change. Addressing these challenges has been identified as an international priority by the International Panel on Climate Change (IPCC), stating that ''global urbanization in its current state, may be the greatest deciding factor of aggravated hydrospheric and atmospheric perturbations, for adverse effects on the biosphere and for significant geochemical changes'' (IPCC, 2013). Measures thus need being implemented within the urban context. Amongst the core measures has been to emphasize the co-evolution of built and green-blue infrastructure in future planning of human habitat (Berg, et al., 2013). Green-blue infrastructure is a term denoting a wide range of phenomena; of particular importance within an urban context are green-blue roofs. This importance stem both from their capacity to improve experiential living-conditions within densely populated areas and – of most interest within the context of this paper – shear stormwater handling potential.

Research has supported the use of green-blue roofs within the urban environment as a tool for urban stormwater management. This concerns especially their capacity to reduce and attenuate stormwater runoff to alleviate the effects of urban flooding events (Bengtsson, Grahn and Olsson, 2005; Vanwoert et al., 2005; Mentens, Raes and Hermy, 2006). In the case of major rain events, green-blue roofs can be a tool in the prevention of sewer overflow by delaying runoff for an extended period and at a lower rate of flow (Getter, Rowe and Andersen, 2007). Reduced stormwater runoff stems from several sources, such as the utilization of green-blue roof evapo-transpiration, soil and drainage medium retention and water harvesting by plants and grey water systems. Within all green-blue roof systems, redundant water is stored in plants, soil and soil medium where it is retained before evaporation or proceeding to the drainage layer. Especially in dense urban environments – where space is limited and roofs account for approximately 40–50% of total surface area – green-blue roofs have the potential to provide significant benefits in stormwater management (Berretta, Poë and Stovin, 2014).

This paper addresses the introduction of green-blue roof infrastructure in urban-rural landscapes, by mapping the technical knowledge and application within the Nordic environment with particular concern for their stormwater retention capacities. The objective has been to review green-blue roofs as an opportunity to reclaim land lost to development and sprawl, and as a first-line of defence to projected increases in precipitation brought on by climate change. Original climate mapping of Norway, Sweden, Finland and Denmark under the Köppen-Geiger classification system is also presented to inform future green-blue roof research within the Nordic countries. Knowledge gaps within the research literature are identified as they pertain to Nordic climates and recommendation are made for further development of research in this field.

According to the research identified, green-blue roofs have been found economically beneficial, for their water retention capacities, their insulationary effects and their vegetation's positive influence on biodiversity and human well-being. Green-blue roofs are found to be economically favourable for cities in particular due to their performance in stormwater management (Janssen, 2014). Equally, green roofs constitute an essential green-blue infrastructure strategy within compact and established urban areas (Delshammer, 2014). Historically, the Nordic countries have used vegetation to increase the thermal insulation of vernacular architecture – in Norway, this has been a standard practice at least since the Viking age (~AD 793–1066) (Berardi, GhaffarianHoseini and GhaffarianHoseini, 2014; Stewart, 2013; Coutts, et al., 2013). Continually in use, traditional sod green roofs have provided added protection for cold climates (Stewart, 2013). In addition, green-blue roofs have been found to increase biodiversity in urban environments (Berardi, GhaffarianHoseini and GhaffarianHoseini, 2014) and even improved perceived qualities of human life (Tzoulas, et al., 2007).

In the late 1800s and early 1900s, the introduction of concrete slabs in flat roof construction led to the development of various new green roof innovations in Europe and North America (Stewart, 2013). By the beginning of the 20th century, the use of green roofs was reinvigorated when Le Corbusier included them in the five points of modern architecture (Le Corbusier, 1923; Eisenman, 2006). By the 1970s, green roofs were becoming popular throughout German-speaking countries (Dunnett and Kingsbury, 2008) and by 1989 there was an estimated 10 million green roofs in Germany (Stewart, 2013).

Within the building industry green roofs are increasingly being used as both a roofing solution with aesthetic value and as a practical stormwater management tool (hereafter green-blue roofs). Today, green-blue roofs are promoted for their adaptive capacity in alleviating the stormwater impacts of climate change within the urban environment (Villarreal, Semadeni Davies and Bengtsson, 2004; Vanuytrecht, Van Mechelen and Van Meerbeek, 2014; Lee, et al., 2013; Webb, 2012). Specialized companies have been established with a wide range of sophisticated systems intended to utilize the advantages of green-blue roofs. While the performance of traditional sod roofs within the Nordic countries is well understood, research is now focusing on how a Nordic climate effects the stormwater performance of green-blue roofs within the urban environment. No cohesive analysis of conducted research seems, however, to have been carried out.

In light of the potentially central importance of green-blue roofs within a Nordic urban context, this paper addresses the following research questions:

- What does the research literature reveal on the subject of the potential role of green-blue roofs within a Nordic urban environment?
- What are the potential implications for stormwater handling within this context?
- What knowledge gaps can be identified within the research literature concerning green-blue roofs' stormwater handling capacities within the Nordic urban context?

To address these research questions, the literature reviewed include articles on vegetative, water retentive and isolative properties as they pertain to green-blue roofs within the Nordic environment. Questions concerning how newer extensive roofing solutions will perform and adapt to Nordic climatic conditions are equally investigated.

Methodological approach

The research carried out has been based on a scoping literature review using the most relevant databases and search engines. In addition, a climate adaptation mapping of the Nordic countries was worked out to establish key characteristics and major framework conditions specific to the region.

Scoping literature review

As commented by Arksey and O'Malley, scope studies have so far received little attention in the literature (2005). As described by Mays, Roberts and Popay (2001), scope studies "aim to map rapidly the key concepts underpinning a research area and the main sources and types of evidence available, and can be undertaken as stand-alone projects in their own right, especially where an area is complex or has not been reviewed comprehensively before". Based on this definition, Arksey and O'Malley (2005) identify four common reasons for undertaking a scope study, notably 1) to examine the extent, range and nature of research activity, 2) to determine the value of undertaking a full systematic review, 3) to summarize and disseminate research findings, and 4) to identify knowledge gaps in the existing literature. It is mainly the first and the fourth of these reasons for undertaking a scope study that has motivated the research reported within this paper. The ambition has thus not been to describe the research findings in detail, but rather to map the field of study in order to visualise the range of material available and direction of research effort identified. The limited examination of existing research within the field of study, in addition to the heterogeneity of the research, motivates this approach as a useful way of mapping the field of study. In addition, the broad approach permits for identifying important gaps in the literature.

The research is limited by only covering research presented in English and Norwegian. Web of Science, Scopus, Google Scholar, American Society of Civil Engineers (ASCE) Library, Oria (Norwegian library database), BIBSYS (Norwegian library database), SINTEF Building and infrastructure Project database and DIVA (Digitala Vetenskapliga Arkivet) were utilised for the search. Keywords included green roof(s), cold climate, blue-green roofs, green-blue roofs, blue-green infrastructure, green-blue infrastructure, extensive roof(s), intensive roof(s), sedum roof(s), stormwater roof(s), green roof(s) insulation, green roof retention, green roof vegetation, green roof rain, green roof freezing, green roof precipitation and green roof snow. In addition, citation chaining as described by Ellis (1989) was employed for articles proving of particular relevance to the research.

Green-blue roofs and the Nordic climate – climate adaptation mapping

As a first step to inform the suggested research identified within this paper the authors have mapped the relevant Köppen-Geiger climate classifications identified, within the Nordic countries of Norway, Sweden, Finland and Denmark. Due to limitations in data, Iceland was excluded from this map. The calculations and visualization of the map were undertaken in ArcGIS ArcMap. Data was collected from gridded temperature maps published by Tveito, et al. (2000) to create the Köppen Climate Classification map for Nordic Countries shown in Figure 1. The gridded map has a spatial scale of 1x1 km². Calculations were performed on ESRI grid ascii files within the ArcGIS ArcMap spatial analyst tool. Cell statistics were used to find the maximum and minimum mean temperature of all 12 months in each grid cell for the normal period 1961–1990.

Two gridded maps were created to identify both the maximum and minimum mean temperature then cross referenced to establish the different climatic regimes. The Nordic countries all fall within the categories illustrated within Table 1. For ease of reference these categories are relisted below:

C: Maritime temperate climate:

- Average temperature high above 10 °C during warmest months and averaging between-3 °C and 18 °C during the coldest monthly periods.

D: Continental climate:

- Average temperature high above 10 °C during the warmest months and averaging below-3 °C during coldest monthly periods.

E: Polar climate

- Average temperatures below 10 °C during all 12 months of the year.

It should be noted that since the Köppen-Geiger categories only states "above" or "below" temperatures, each climatic category was determined by the criteria equations listed below applied to the 30-year average:

C: T(average) max ≥ 10 °C and -3 °C ≤ T(average) min < 18 °C

D: T(average) max ≥ 10 °C and T(average) min < -3 °C

E: T(average) max < 10 °C

Theoretical framework – the nature of Nordic climate

Nordic climate

The Köppen-Geiger classification system is divided into five main groups with several types and subtypes. Nordic climates, relevant to green-blue roof application have been identified within this research as Type C within the sub-group specification of Maritime sub-arctic climates / Sub-polar oceanic climates Type (Cfc) and Type D Continental/Micro-thermal. While Type E Alpine/Polar climates are classified as Tundra climate, the extreme and inhospitable nature of these environments render the climate irrelevant for the purposes of this research. The three climate groups covered by Nordic climate are characterized in Table 1 (McKnight and Hess, 2000; Rubel and Kottek, 2010).

Table 1
Nordic climate classification (Köppen-Geiger)

CLIMATE GROUP	Sub-group specification	Latitude	Avg. temp. Warmest months	Avg. temp. Coldest months	Climate Description
C: Temperate/ Mesothermal	(Cfc): Maritime subarctic/ Sub-polar oceanic climates	Between 45° and 55° Up to 63°N in coastal Norway	>+10 °C	>-3 °C	Mild with no dry season, cool summer
D: Continental/ Microthermal	(Dfa, Dfb, Dwa, Dwb): Humid continental (Dfc, Dfd, Dwc, Dwd): Subarctic	North of 40°	>+10 °C	<-3 °C	Humid with warm to hot summer. Severe dry winter Severe dry winter, cool summer
E: Alpine/Polar	(ET): Tundra climate		<+10 °C	–	Found within the polar regions or in extreme altitudes, above the tree line

Understanding the unique climate conditions of an environment is essential in the successful selection and optimal performance of green-blue roofs within the Nordic climate. The following sections provide an overview of research into green-blue roof functions, advantages and challenges as they pertain to cold climates. Knowledge gaps are then identified. The main issues identified in the literature include structure, vegetation, insulation and water-related issues.

Climate classification map for Nordic countries

Figure 1 shows all three of the Köppen-Geiger subcategories identified in Table 1 and where they occur within each country. While classified under differing categories, Denmark (Maritime temperate) and Finland (Continental) are shown to be mono-climatic countries within the characterization of Köppen-Geiger's classification system.

Figure 1
Climate Classification map for Nordic Countries according to the Köppen-Geiger system – all cities above 100.000 inhabitants marked out (2016).

Sweden and Norway comparatively are shown to have the full range of cold climates identified within the Nordic environment by the Köppen-Geiger system. Sweden's climatic regions are localized within the country and graduate from the warmest coastal areas of the southern Swedish tip to the polar/alpine northern border with Norway.

Within Norway the identified climatic zones do not graduate as longitude increases – as was found in the other Nordic countries mapped – but rather are more greatly influenced by coastal exposure, topography and elevation. This provides unique challenges not only in selecting the appropriate green-blue roof solutions for a given environment, but these challenges are compounded by the impact of seasonal sun exposure and varying duration of growing season due to both seasonal sun exposure and temperature.

It should also be noted that the research presented is equally relevant to heavily developed areas that fall outside the somewhat narrow definition of urban; i.e. industrial parks and airports. This follows the EEA (2010) definition of urban areas, cities or towns. The Climate classification map also identifies urban centres, as have been defined within this of urban as cities with population sizes over 100.000 inhabitants. The large cities in the Nordic countries relevant for using green-blue roofing solutions are to be found in climate groups C and D.

Green-blue infrastructure – definition

Berg, et al. (2013) outlines an understanding of the impact of green-blue (soil-water-plant systems) infrastructure as being in the contextual interactions between buildings, urban activity and the climatic environment. The European Commission emphasizes the ''spatial structures of natural and semi-natural areas and environmental features, which enable citizens to benefit from its multiple services'' (EGCA, 2013). Within the United States, green-blue infrastructure has been defined as the combination of natural, semi-natural and built networks of ecological systems which occur around and between urban areas at varying spatial scales providing multi-functional uses (Tzoulas, et al., 2007). According to the authors of this paper, however, within the theoretical field of landscape architecture the concept of green-blue infrastructure is poorly defined. In the present paper, green-blue infrastructure is understood as comprising "green solutions" (gardens, roofs, terraces, parking spots and other green areas) integrated with "blue solutions" (drainage systems, ponds, sewer systems). This understanding equally applies to green-blue roofs.

Functionalities, advantages and challenges

Extensive research has evaluated the performance of the green-blue roof related functions of insulation, water retention and vegetation, which are of particular relevance within the context of Nordic climates. These characteristics as well as their advantages and challenges are listed in Table 2. The findings section of this paper is organised according to the three categories of function thus identified.

Table 2
Green-blue roof advantages and challenges

Function	Advantage	Challenge	Sources
Vegetation	Increased biodiversity, providing natural habitat for animals, insects and vegetation	Selection of native vegetation and assuring establishment, avoiding alien species	Berardi, GhaffarianHoseini and GhaffarianHoseini (2014); Bianchini and Hewage (2012); Emilsson (2008)
Insulation	Reduction of heat transfer through roof, sound insulation	Dependent on selected green-blue roof and climatic conditions	D'Orazio, Di Perna and Di Giuseppe (2012); Jaffal, Ouldboukhitine and Belarbi (2012); Getter, et al. (2011); Castleton, et al. (2010); Pierre, et al. (2010); Bass (2008)
Water retention	Reduction of water runoff volume, stormwater management	Adopting solutions to local climatic conditions	Bengtsson, Grahn and Olsson (2005); Mentens, Raes and Hermy (2006); Vanwoert, et al. (2005)

Attributes of extensive roofs

Green roofs (and correspondingly green-blue roofs) are most often categorized into extensive roofs (60–150 kg/m^2), semi-intensive roofs (120–200 kg/m^2) and intensive roofs (above 180 kg/m^2) (Noreng, et al., 2012). The focus of the research presented in this paper is extensive roofs. Intensive and semi-intensive roofs will not be addressed. The main reason for this delimitation is the fact that extensive roofs can be used within the context of already existing buildings. In urban areas, much (if not the main part) of the built environment is already constructed. Addressing stormwater issues through the use of green-blue roofs within such environments renders the study of extensive roofs most pertinent, an insight which is found to be common in the research literature on the subject. Sedum is an example of extensive roof (*ibid.*).

A green-blue roof system is covered partially or completely with layers of living vegetation and can be installed on top of conventional flat roofs or pitched roofs. As shown in Figure 2, the structure of green-blue roofs consists of a vegetation layer, growing medium (or soil layer), a drainage layer and a membrane layer, which serves as filter and waterproofing layer (Castleton, et al., 2010). Often the structural varies depending on system and layers maybe omitted or required, such as root barriers or irrigation systems (Palla, Gnecco and Lanza, 2009; She and Pang, 2010).

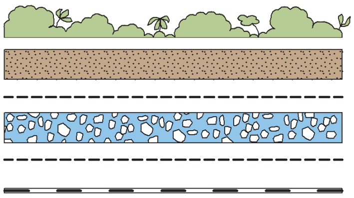

Figure 2
Green-blue roof structure

Some of the layers of the green-blue roof system can be multi-functional and can be applied on different structures and surfaces considering the materials and the age of the building's construction (Noreng, 2013; Noreng, et al., 2012; Hopkins and Goodwin, 2011; Krohn and Noreng, 2009).

Findings

The literature review identified three main functions sought after when introducing green-blue roofs, notably vegetation, insulation and water retention (Table 2). The findings section is organised according to the three categories of function here in identified.

Vegetation

The city is a living ecosystem. Reduced space available for planting or biomass in most urban ecosystems leads, however, to reduced levels of photosynthesis and carbon/oxygen exchange in the atmosphere (Berg, et al., 2013; Hopkins and Goodwin, 2011; Noreng, et al. 2012; Thodesen and Busklein, 2012). The footprint of the city reduces living space for natural vegetation and creates a need for greening initiatives. Green-blue roofs can be part of an urban green network (Hopkins and Goodwin, 2011). The selection of native vegetation on green-blue roofs can equally provide habitat for species that have lost their natural environment to encroaching development (Noreng, et al., 2012).

Growing season

The selection of the appropriate vegetative cover for a specific roof is essential to the roof's successful establishment and performance, and climate is the primary determiner of proper species selection. The geography of latitude, altitude, terrain and large bodies of water primarily determine climatic conditions, which have been classified within the Köppen-Geiger climate classification system. This system defines zonal boundaries of climate through the assessment of native vegetation distribution combined with average seasonal temperatures and precipitation (McKnight and Hess, 2000). Within the Nordic environment the growing season, also called the frost-free season, is present in Köppen-Geiger's Type C and D climates (McKnight and Hess, 2000), while Type E climates experience frost year around. In the following, we understand the length of growing season as the days when average temperature is above the threshold at which vegetation will germinate and grow.

Research has emphasized the importance of climate consideration when selecting plant types for a given ecosystem (Getter and Rowe, 2006; Berardi, GhaffarianHoseini and GhaffarianHoseini, 2014). Proven mixtures of plants are commonly used for extensive roofs within Nordic climates is given by Emilsson and Rolf (2005). Test results have found that prefabricated vegetative mates achieve a higher overall cover in the first year than shoots or plug methods. The Emilsson and Rolf (2005) study suggested that there were no identifiable advantages for the use of plug plants in a Swedish climate. Plug and shoot establishment methods were found to have a mean cover of 50–60% (Emilsson and Rolf, 2005). Vegetative mats, when the standard mix was applied retained a greater than 80% plant cover, well within the range of the FLL Guidelines (2008) requirement of 60% (Emilsson and Rolf, 2005). Research has also found that sedum has a shorter root structure and is compatible with limited water sources (Emilsson, 2008; Getter and Rowe, 2006), while prairie and grassland species require sufficient irrigation and soil layer depth, but retain more water (Sutton, et al., 2012). Various studies have found that plant diversification helps to maximize the effectiveness of green-blue roofs (Wolf and Lundholm, 2008). Research has also shown that green roofs have been colonialized spontaneously by airborne seeds and animals even when not specifically planned as living biodiversity havens (Hopkins and Goodwin, 2011). It should also be noted that as green roofs could be spontaneously colonized, there is also a danger of spreading alien species to surrounding nature and affecting natural biodiversity (Noreng, et al., 2012).

Knowledge gaps

There is a need for research about the comparative varieties of plant types, to provide guidelines for selection of the most climatically appropriate plants for a given site (Getter and Rowe, 2006; 2008). Further research should also consider different possible soil depths, water availability and plant density, as well as how these variables contribute to improved or compromised performance within the Nordic climate (Berardi, GhaffarianHoseini and GhaffarianHoseini, 2014).

Temperature

Temperature is an important factor influencing the performance of green roofs (Jaffal, Ouldboukhitine and Belarbi, 2012). The vegetation layer is most affected by temperature and fluctuations because different plant species require different climate zones due to differing cold and heat tolerances (Boivin, et al., 2001). Therefore, it is important to choose plants that can tolerate the unique climate conditions of a site both above and below ground (Guckenberger Price, et al., 2011).

In cold temperatures, the growing medium has to be thicker to prevent plants suffering from deep freeze related injuries (Bass, 2008). A minimum depth of 10 mm (4 inches) of substrate is recommended in northern latitudes (Boivin, et al., 2001). Newly established species are especially vulnerable to freeze related injuries (Emilsson and Rolf, 2005). Nevertheless, daily temperature variations can be more damaging to perennials than low temperatures, which are more often seen in Type D Continental/Micro-thermal climate zones (Boivin, et al., 2001). Sensitivities in variations to winter temperature have been attributed to conditions where little or no insulative snow layer in combination with sunny conditions exacerbate vegetation's exposure to extremes (Getter, et al., 2011). During winter months when both green roofs and conventional roofs are covered with snow, the top insulation and roof membrane temperatures are nearly identical, (Liu and Baskaran, 2003; Getter, et al., 2011) providing vegetation with isolative temperature control.

Knowledge gaps

Further research is recommended into the thermal performance of varying systems in differing moisture conditions, temperature variations and winter conditions characteristic of Nordic climates. Pierre, et al. (2010) make the recommendation for further development and refinement of methods to account for these variables.

Durability

When constructing to optimize durability, it is recommended to plant several species with varying properties, since variations in air, temperature and precipitation effect the growth environment for plants, Nagase and Dunnett (2010) found that "diverse plant mix was more advantageous than a monoculture in terms of greater survivability". Allowing a wide composition of species provides greater growth during the growing season (Noreng, et al., 2012). Prefabricated vegetated mats provide immediate and usually greater cover than other methods because of their established root system and canopy. Moss provides additional advantages in green-blue roofs as an addition to the total cover, absorbing water, extending the growing season, and provide an evergreen appearance within cold climates. However, the incorporation of moss should be balanced with other plant species as moss attracts birds that dig into substrate in search of food and nesting materials (Emilsson and Rolf, 2005).

It should also be noted that in Nordic climates, road de-icing salt is commonly used for keeping streets clear of ice. Green roof research indicates that plants farthest from the road had higher mean health scores and a greater percentage of healthy plants than plants closer to the highway. Nevertheless, road salts do not have overall effect on survival rates (Whittinghill and Rowe, 2011).

Knowledge gaps

Further research is needed to evaluate undertaken to evaluate the performance and durability of varying plant mixtures and installation methods across the range of cold climate conditions found in the Nordic countries. Relevant to this study is to consider the variability of climates, freeze thaw conditions, temperature extremes and the limitations of water retention / green-blue roof saturation during winter periods. See Figure 3.

Figure 3
Extensive green-blue roof (sedum roof) in Trondheim, Norway, before and after a rough winter. The right part of the picture taken one year after the left part, both approx. 1 July.
PHOTO: TORE KVANDE

Insulation

Little research has been identified addressing specifically the insulation capabilities of green-blue roofs. More has been done within the context of green roofs, and the results from this research are pertinent to the understanding of green-blue roof functions.

Thermal insulation capabilities

Thermal insulation capabilities of green roofs are well studied and are noted for protecting the roof slab from extreme temperatures and fluctuations. This protection is provided by a number of thermal phenomena, such as solar shading, evapotranspiration, high plant albedo and soil thermal resistance (D'Orazio, Di Perna and Di Giuseppe, 2012; Jaffal, Ouldboukhitine and Belarbi, 2012; Liu and Baskaran, 2003). This in turn influences a building's energy demand and indoor thermal conditions by as much as three times greater efficiency than a conventional roof during summer months (Jaffal, Ouldboukhitine and Belarbi, 2012)

Research has confirmed the principles of ancient Nordic practices by demonstrating that green roofs require less power than conventional built-up roofs to maintain thermal comfort inside, especially in cold climates where these effects can be notable (Jaffal, Ouldboukhitine and Belarbi, 2012; Pierre, et al., 2010). During Nordic winters – when there's a substantial difference between interior and exterior temperatures – heat loss increases through the roof. In such conditions, green roofs can act as thermal barriers to reduce heat transfer (Bass, 2008). Green roofs also have low thermal conductivity and high thermal mass that reduces thermal dispersion in wet or saturated conditions (D'Orazio, Di Perna and Di Giuseppe, 2012). In winter, the thermal performance of a building can also be further improved by trapping snow within the vegetation layer (Pierre, et al., 2010).

The insulative impact of green roofs is often substantial in central Europe and other cold climate zones. There are, however, higher U-value requirements for roofs mitigating such impacts within Norway's Technical Regulations TEK17 (2017). The requirements of Sweden and Finland equally stand out as compared to those operating within the EU. It should also be noted that green roofs are not given a standard U-value because the additional level of insulation provided is dependent of several factors. Moisture level also greatly determines insulation effectiveness, and this is enormously dependent on factors within local climate (D'Orazio, Di Perna and Di Giuseppe, 2012).

While U-value calculations have proven elusive, in North America a web calculator has been developed thru collaboration between the University of Toronto, Portland State University and Green Roofs for Healthy Cities. This calculator allows comparison of the annual energy performance for buildings with green roofs, dark roofs or white roofs, in both new and old construction, across building typologies (Sailor, 2008; Portland State University, 2015). The calculator also considers weather data and precipitation according to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standards (Berardi, Ghaffarian Hoseini and Ghaffarian Hoseini, 2014). ASHRAE is an American trade group that publishes guidelines and standards for regulatory and legislative uses related to building systems, energy efficiency, indoor air quality, refrigeration and sustainability (ASHRAE, 2015). Since 2007 this calculator has become part of the standard US Department of Energy's EnergyPlus model (Sailor, 2008). Unfortunately, this tool is limited in its availability to only US cities.

Knowledge gaps

Research is needed to evaluate the potential benefits and limitations of expanding the EnergyPlus/ASHRAE green roof calculator or likeminded tool for use within the Nordic market. Furthermore, to determine what, if any impact green roofs would have on U-values, in addition to the existing requirements already existing within the Nordic countries. In particular, the potential insulative benefits and limitations of green roofs in cold climate and how they may be incorporated into or accounted for in existing insulation standards would be valuable.

Urban Heat Island Effect

While not of particular relevance to the Nordic countries, the Urban Heat Island effect (UHI) is a phenomenon where the temperature of large cities is higher than surrounding rural areas. Dark surfaces on top of buildings, walls and pavements store solar energy and release it back into the atmosphere (Hopkins and Goodwin, 2011). The lack of vegetation in cities is credited as one of the greatest factors effecting increases in urban temperatures (Alexandri and Jones, 2008). These effects can result in the increase of energy consumption, particularly during warm periods when air conditioning is required (Hopkins and Goodwin 2011; Bass, 2008). Green roofs reduce urban temperatures (Ouldboukhitine, Belarbi and Sailor, 2014) and mitigate the UHI effect thru evaporation, evapotranspiration and decreased albedo effect (Bianchini and Hewage, 2012). While, the impacts of greening building surfaces on UHI is often cited as a benefit of green roof infrastructure in urban environments (Hopkins and Goodwin, 2011), colder climates benefit the least because they experience the smallest reductions in UHI temperature (Alexandri and Jones, 2008; Teemusk and Mander, 2007).

Water retention

Retention capabilities

The retention capability of vegetative roofs in Norway is of particular interest because of their ability to manage stormwater runoff through flow delay and water retention within the urban environment (Time, 2014; Berretta, Poë and Stovin, 2014; Noreng, et al., 2012; Gregoire and Clausen, 2011). Much research has been done on the effects green-blue roofs have on the quantity of water runoff from individual rain events (Thodesen and Busklein, 2012; Palla, Gnecco and Lanza, 2009; Getter, Rowe and Andersen, 2007; Teemusk and Mander, 2007; Bengtsson, Grahn and Olsson, 2005; Vanwoert, et al., 2005). Green-blue roofs delay and reduce the peak discharge of rain water off a roof as compared to a traditionally built hard surface roof. Dependent on the build-up of the green-blue roof and within given conditions, a portion of the rain water is detained, and a portion of the water is retained to later evaporate or transpire (Berndtsson, 2010). Green-blue roofs have been shown capable of diminishing potential water runoff by more than 50% (Mentens, Raes and Hermy, 2006). Figure 4 illustrates this phenomenon (Noreng, et al., 2012).

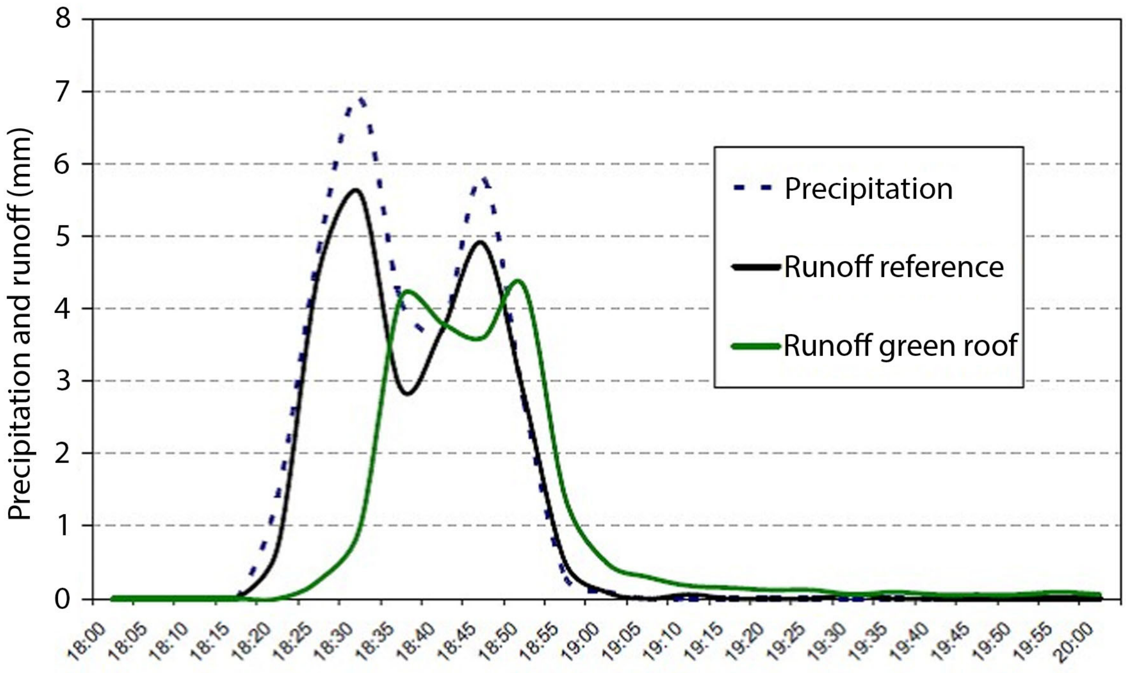

Figure 4
Runoff volumes of green-blue roof and conventional roof (Braskerud, 2010)

This delay can significantly reduce the peak rate of runoff during short storm events. While hydrological modelling has demonstrated that with the widespread application of green-blue roofs in an urban environment, this phenomenon provides significant impact on stormwater runoff and proves a useful tool in the management of stormwater runoff in short term events (Carter and Jackson, 2007).

Knowledge gaps

Further research must be undertaken to establish what impacts Nordic conditions have on the performance of green-blue roof water retention. In particular, research must be undertaken to understand the impacts snow and ice, freezing and thawing cycles have on green-blue roof retention capabilities.

Irrigation

There is great variability in the water tolerance of plants and therefore also a varying need for irrigation depending on selected vegetative material. It is important to choose the most appropriate plants for local climatic conditions. The medium of green-blue roofs exposed to direct sunlight will dry out more quickly, such conditions require a high tolerance of desiccation within the vegetative layer or a supplementary supply of water (Noreng, et al., 2012). If the humidity in the air is low, green roofs may need a regular supply of water to compensate for the lack of moisture in the air (Hopkins and Goodwin, 2011).

If local precipitation is too great – resulting in standing water – the roots in the vegetation layer may rot. It is therefore crucial for the excess water to drain away expediently. Alternatively, if the drainage is too efficient plants may be deprived of an adequate water supply. Therefore, drainage systems within a given green-blue roof must be adjusted to the precipitation averages of the local climate to prevent the drying out or drowning of vegetation (Noreng, et al., 2012).

Knowledge gaps

Challenges in research within the Nordic context currently highlight the lack of standards or systems to follow in the adjustment of drainage systems within a given green-blue roof to the localized precipitation averages of a site.

Retention rates

Reviewed studies have shown the effects of green-blue roofs on stormwater runoff, but the relative impact of an individual green-blue roof solution is highly dependent on the number of layers and type of materials, depth and composition of growing medium selected (Berretta, Poë and Stovin, 2014; Berndtsson, 2010; Villarreal, Semadeni-Davies and Bengtsson, 2004). In general, intensive green-blue roofs have greater retention rates than extensive green-blue roofs (Mentens, Raes and Hermy, 2006), but increased organic matter and microspores in substrate can also increase water-holding capacity of a green-blue roof (Getter, Rowe and Andersen, 2007). Retention rates are highest for minor rain events and minimized for heavy or extreme events due to the substrates' limited storage capacity as once saturated, the retention and runoff delay is negated (Getter, Rowe and Andersen, 2007; Mentens, Raes and Hermy, 2006). This phenomenon was illustrated by Mickovski, et al., (2013) and is shown in Figure 4. Water retention is a function of time and increases asymptotically with thickness, most often in relation to the substrate. By dividing substrate into three groups (<50, 50–150, >150 mm), Mentens, Raes and Hermy (2006) summarizing German studies, showed a general runoff reduction during warm periods being 62%, 70% and 80% respectively. This was illustrated by Metselaar (2012) with a spectrum of substrate performances ranging in annual median values of 55% to approximately 75%. It should be noted that function of substrate depth has a point of diminishing returns in regard to water retention, and performance does not show a marked increase once substrate depth exceeds 400 mm (Metselaar, 2012).

Retention values also vary due to roof geometry; as slope increases, retention decreases (Getter, Rowe and Andersen, 2007; Villarreal, Semadeni-Davies and Bengtsson, 2004). Additionally, structural characteristics like the vegetation cover, type of vegetation, roof position and roof age will also affect water retention performance (Berndtsson, 2010). Vegetation also plays an important role in retention rates, because different plants have different retention capabilities (Thodesen, 2012; Emilsson, 2008). The greater the surface of the plants parts, the more water the plant can absorb and delay (Noreng, et al., 2012). Well established vegetation with good surface coverage increases transpiration and also prevents wetting during minor rainfall events (Berretta, Poë and Stovin, 2014).

The climatic factors which influence water retention capacity and run-off primarily depend on weather conditions including the distribution of precipitation, the length of time preceding dry periods, season/climate (air temperature, wind conditions, humidity) and characteristics of a rain event (intensity and duration) (Berndtsson, 2010). Green-blue roof retention capacity has been found to be most efficient during summer months, while performance diminishes during the winter season (Metselaar, 2012).

Seasonal retention has been quoted by Berndtsson (2010) as averaging 19% in February and increasing up to as much as 88% in June, it should be noted that this performance range is dramatically impacted by the specifics of a given green-blue roof build-up. The German FLL Guidelines (2008) of green-blue roof construction provide yearly retention values that start at 40% and increase every 10 mm of substrate thickness by roughly 1%, maxing at a 70% retention rate for substrates between 250 mm up to 500 mm.

Knowledge gaps

Further research must be carried out to determine the retention performances throughout extremes of Nordic seasonal weather and to provide applicable retention performance standards for specific Nordic climatic conditions. The German FLL Guidelines (2008) outline a common standard across Europe regarding green-blue roof installation and performance. Despite this, the guidelines fall short in addressing the performance requirements and expectation of green-blue roofs in snow and freeze/thaw conditions. These knowledge gaps need to be addressed and incorporated into these standards.

Water retention in cold climates

Research has shown the efficiency of green-blue roofs in summer to retain short, stormwater events, the warmer the season the higher evapotranspiration and the faster the retention capacity is able to regenerate (Mentens, Raes and Hermy, 2006; Villarreal, Semadeni-Davies and Bengtsson, 2004). Research has also shown that retention is dependent on the season and that retention capacity decreases during winter months (Metselaar, 2012).

There is not a standard definition for seasons within green-blue roof research and authors of seasonal studies define seasons in different ways, making comparison of results difficult. Mentens, Raes and Hermy (2006) summarized 18 different German studies and defined three seasons; “Warm”: 1 May–30 September, “Cold”: 16 November–15 March, and

"Transitional" seasons: 16 March–30 April and 1 October–15 November. Retention rates of seasonal runoff were; 70% for the "Warm" season, 49% for "Transitional" seasons, and 33% for the "Cold" season. It should be noted that Mentens, Raes and Hermy (2006) found a 37% average decrease in retention performance of green-blue roofs during winter conditions.

In the assessment of 7 extended water retention studies between 2–17 months (Bengtsson, Grahn and Olsson, 2005; Vanwoert, et al., 2005; Bliss, Neufeld and Ries, 2009; Carter and Rasmussen, 2006; DeNardo, et al., 2005; Monterusso, et al., 2004; Moran, Hunt and Smith, 2005). A Swedish study (Bengtsson, Grahn and Olsson, 2005) found that on a monthly basis the lowest runoff reduction rates were obtained in February (19%) and the highest in June (88%). In comparison, clear seasonal effects in relative runoff reduction compared to rainfall have been found between the months of November through March (Kohler, et al., 2001). These findings are confirmed by Bengtsson, Grahn and Olsson (2005). In these, the average water retention rate during the "cold" season of November thru March was found to be 33.4%, and congruent with the findings of Mentens, Raes and Hermy (2006).

Teemusk and Mander (2007) have also undertaken studies of green-blue roof runoff under winter conditions and during snow melting. Two melting periods where distinguished; a 1-day period of melting snow cover and a 12-day period during which the frozen water within the substrate layer melted.

Knowledge gaps

The Teemusk and Mander (2007) study was extremely limited and the researchers, as well as subsequent reviewers, have cited the need for more studies of green-blue roofs under snow and freeze/thaw conditions to quantify how green-blue roofs perform in winter (Berndtsson, 2010; Teemusk and Mander, 2007). Extensive research is needed to be undertaken to explore the potential to improve winter season retention rates of extensive green-blue roofs if they are seriously to be considered as a tool for stormwater management within the Nordic urban environment.

Conclusions

The literature review reported on in this paper set out to address, firstly, what the research literature reveals on the subject of the potential role of green-blue roofs within a Nordic urban environment, secondly, what the potential implications for stormwater handling within this context were, and, finally, what knowledge gaps could be identified within the research literature concerning green-blue roofs' stormwater handling capacities within the Nordic urban context. In the following, we summarize the findings concerning each of these research questions successively.

The research literature on green-blue solutions in general was found to be rich. Not surprisingly, it proved more limited concerning the specific conditions of green-blue roofs having to address within a Nordic urban environment. Three main functions were found to be sought after when introducing green-blue roofs, notably vegetation, insulation and water retention. Firstly, some research concerning the establishment of plants has been carried out, alongside research on type of plants, plant diversification and the potential for unintentional colonizing by plants of green-blue roofs, and from such roofs to the environment. The research identified further maintain that cold climates necessitate thicker growing mediums than other climates in order to protect the plants from freeze injuries. The effects of such injuries have been found to be mitigated through diversification of the species introduced. Of particular interest in the Nordic countries has been the influence of road de-icing salt on green-blue roofs. Secondly, little research has been identified addressing specifically the insulation capabilities of green-blue roofs. More has been done within the context of green-blue roofs, and the results from this research are pertinent to the understanding of green-blue roof functions. The research identified confirms the principles of ancient Nordic practices by demonstrating that green roofs require less power than conventional built-up roofs to maintain thermal comfort inside, especially in cold climates where these effects can be notable. Technical regulations, however, especially concerning U-value requirements, make the potential for employing green-blue roofs on the basis of their insulatory effects challenging in all the Nordic countries. Thirdly, and generally, green-blue roofs have been shown capable of diminishing potential water runoff by more than 50%. This delay can significantly reduce the peak rate of runoff during short storm events. Research has shown that retention is dependent on the season and that retention capacity decreases during winter months. The influence of Nordic climate conditions for this performance seems, however, sparsely researched.

Concerning the implications of the research reviewed, it suggests that, at the performance and component level, the use of green roofs as a green-blue infrastructural solution may be used as an integral component for urban climatic adaptation in Nordic climate conditions. Green roofs provide an immediate impact when trying to incorporate green-blue infrastructure into the planning, design and management of existing dense, urban environments. They are a first-line of defence to projected increases in stormwater pressures within urban environments.

Several knowledge gaps were identified. The most important of these are in the following grouped according to the major findings of the review carried out. Concerning planting and plant conditions, the following can be outlined:

- There is a need for research concerning comparative varieties of plant types, soil depths, water availability and plant density to provide functional guidelines for practitioners within the Nordic climate.

- Further research is equally recommended on subject of the thermal performance of varying systems in differing moisture conditions, temperature variations and winter conditions characteristic of Nordic climates.
- Concerning the performance and durability of varying plant mixtures and installation methods across the range of cold climate conditions found in the Nordic countries research proved limited.

The review of papers concerned with questions of thermal insulation revealed the following knowledge gaps:

- Determine what, if any, impact green-blue roofs would have on U-values, in addition to the existing requirements already existing within the Nordic countries.
- In particular, the potential isolative benefits and limitations of green roofs in cold climate and how they may be incorporated into or accounted for in existing insulation standards would be of particular value.

On the subject of water retention, the following knowledge gaps were identified:

- Further research is needed to establish what impacts Nordic conditions have on the performance of green-blue roof water retention. In particular, research regarding to understand the impacts snow and ice, freezing and thawing cycles have on green-blue roof retention capabilities.
- There is a lack of standards or systems to follow in the adjustment of drainage systems within a given green-blue roof to the localized precipitation averages of a site.
- Retention performances throughout extremes of Nordic seasonal weather needs being determined. Following this, applicable retention performance standards for specific Nordic climatic conditions ought to be established.

In sum, the limited research on the topic within a Nordic context has rendered the establishment of proper guidelines difficult. In order to address the challenges to which blue-green solutions in general and blue-green roofs in particular are thought to solve, further research is needed within areas pointed out within this paper.

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Biographical information

Bridget Thodesen
Norwegian University of Science and Technology (NTNU),
Department of Civil and Environmental Engineering
Address: Høgskoleringen 7b,
7491 Trondheim, Norway
E-mail: bridget.thodesen@ntnu.no
Phone: +47 930 30 673

Bridget Thodesen is a civil architect with a (M.Sc.) in landscape architecture and (M.Sc.) in urban planning, currently a PhD Candidate at the Norwegian University of Science and Technology (NTNU). Her research has focused on decision processes in the reduction of precipitation and flood risk through climate adaptation of buildings and infrastructure, under the Klima 2050 Centre for Research-based Innovation (SFI).

Biographical information

Tore Kvande
Norwegian University of Science and Technology (NTNU),
Department of Civil and Environmental Engineering
Address: Høgskoleringen 7b,
7491 Trondheim, Norway
Phone: +47 902 55 434
E-mail: tore.kvande@ntnu.no

Tore Kvande is a civil engineer (M.Sc.) and holds a doctoral degree in Building Science from the Norwegian University of Science and Technology (NTNU). He is professor in building materials at NTNU and principal investigator in SFI Klima 2050. His main scientific interest is in the areas of climate adaption of buildings and building design.

Biographical information

Helga Therese Tilley Tajet
The Norwegian Meteorological Institute,
Observation and Climate Department
Address: Henrik Mohns Plass 1,
0313 Oslo, Norway
Phone: +47 229 63 000
E-mail: helgattt@met.no

Helga Therese Tilley Tajet has a M.Sc. in Meteorology and Oceanography. She is working as a climate scientist in the Division for Climate Services at MET Norway. There she analyses past, present and future climate data. She is working with different climate indices. Is in contact with users and works with facilitation of climate data for users.

Biographical information

Berit Time
SINTEF Building and Infrastructure,
Department of Architecture, Materials and Structures
Address: Høgskoleringen 7b,
7034 Trondheim, Norway
Phone: +47 970 72 083
E-mail: Berit.Time@sintef.no

Berit Time is a civil engineer (M.Sc.) in building technology and has a PhD from NTNU in the same field. Her research and experience is within climate adaptation of buildings, moisture in buildings and materials and zero emission buildings. She is a chief scientist at SINTEF Building and Infrastructure and the managing director of the Norwegian Research Centre on Risk reduction through climate adaptation of buildings and infrastructure (SFI Klima 2050).

Biographical information

Jardar Lohne
Norwegian University of Science and Technology (NTNU),
Department of Civil and Environmental Engineering
Address: Høgskoleringen 7a,
7491 Trondheim, Norway
Phone: +47 930 30 673
E-mail: jardar.lohne@ntnu.no

Jardar Lohne, dr. art., is a research scientist within the Department of Civil and Environmental Engineering at the Norwegian University of Technology and Science. Over the latest years, he has published broadly, on themes ranging from theoretical ethics to applied civil engineering. Currently, he is mainly involved in the Research Program SFI Klima 2050.