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Urban Rooftop Agriculture: Challenges to Science and Practice

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Urban green infrastructure includes both natural inputs and artificial supplements, including irrigation, synthetic substrates, and drainage layers. Green infrastructure aims to make cities more resilient and less dependent on outside resource inputs through more efficient use. Over the past 2 decades, these constructed ecosystems have expanded to include green roofs, elevated urban parks, and rooftop vegetable farms. This paper outlines opportunities and challenges for advancing the science of these constructed ecosystems with particular emphasis on rooftop agriculture. Although in concept rooftop agriculture could contribute to urban food security, water management, and biodiversity, research comparing design and management strategies across climate zones and regional economies is necessary to fully integrate ecological understanding into urban planning policy.

Keywords: green infrastructure (GI), urban biogeochemistry, urban ecology, green roof, rooftop agriculture, ecosystem services (ES), urban agriculture (ua)

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INTRODUCTION

Cities are recognized as having environmental footprints extending far beyond their political borders, consuming resources and producing wastes in ways that can globally impact nature and human well-being (Vitousek et al., 1997; Alberti et al., 2003; Grimm et al., 2008). Beginning in the 1990s, this recognition has led to studies of urban biogeochemical cycles, while practices of urban planning and design have applied this knowledge, and explored diverse options for restoring ecological functionality to the built environment (Palmer et al., 2004; Kennedy et al., 2011; Pataki et al., 2011; Pickett et al., 2011). For example, horticultural technologies support the establishment and maintenance of soil-plant systems, such as green roofs, bio-retention basins, and other green spaces constructed on built surfaces, including roofs, pavements, and street-level portions of underground structures (Dunnett and Hitchmough, 2004; Dunnett and Clayden, 2007; Oberndorfer et al., 2007; Driscoll et al., 2015; Lundholm, 2015).

Major strides have been made in the practice of growing drought-tolerant succulents, grasses, and shrubs by using synthetic substrates on top of built surfaces with little or no supplemental irrigation and nutrients (**Figure 1A**) (Dunnett and Hitchmough, 2004; Dunnett and Kingsbury, 2008; Dunnett et al., 2008; Dvorak and Volder, 2010; MacIvor and Lundholm, 2011; Kotsiris et al., 2012; Nektarios et al., 2012, 2014, 2015; Ntoulas et al., 2013b; Van Mechelen et al., 2015). Design approaches have even expanded to include large-scale (e.g., > 2 ha) elevated urban parks (**Figure 1B**) and rooftop agriculture (**Figure 1C**) (Harada et al., 2017; Houston and Zuñiga, 2019). Since the late 1990's, these constructed ecosystems have become integral components of urban "green infrastructure" projects (Lundholm, 2015). The diverse goals of these green infrastructure projects include stormwater management, energy savings, biodiversity restoration, air pollution abatement, crop production, and recycling food waste through composting (Oberndorfer et al., 2007; Berndtsson, 2010; Rowe, 2011; Ahern et al., 2014). There are growing bodies of research relevant to performance measurements and improvements of constructed ecosystems in the fields of plant and soil science, hydrology, and biogeochemistry, while further research is needed for developing best management practices that directly inform urban planning and policy (Pataki et al., 2011; Driscoll et al., 2015; Pataki, 2015).

Novel Ecosystems

An overarching framework of ecological communities represented in green infrastructure is useful for delineating and understanding constructed urban ecosystems. In terms of the intensity of ecosystem modification, urban green infrastructure projects range from remnant natural ecosystems to entirely constructed ecosystems (**Figure 2**). Urban ecosystems are often described as "novel ecosystems" which have no analog in the non-urban environments traditionally studied in the field of ecology (Hobbs et al., 2006; Kowarik, 2011; Perring et al., 2013). For example, remnant natural ecosystems in the urban environment can have distinct species composition and dynamics as the result of unintentional human influence such as the legacy of industrial activities (Kowarik, 2005, 2011). Although the difference between novel and constructed ecosystems is still debated, the concept of novel ecosystem has been used to describe constructed ecosystems as the direct outcome of urban planning and design (Lundholm, 2015; Ahern, 2016; Higgs, 2017). For example, biogeochemical properties of constructed ecosystems are engineered using artificial components such as synthetic substrates, drainage layers, and water-proofing membranes, which alter ecological processes such as movements of water and nutrients across spatiotemporal scales (Berndtsson, 2010; Pataki et al., 2011; Rowe et al., 2014; Fassman-Beck et al., 2015; Harada et al., 2018a,b). These artificial components are studied from various points of view in the disciplines of horticulture, controlled-environment agriculture, and civil and environmental engineering, all of which need to be included in collaborative research if the goal is increased understanding and improved performance of constructed ecosystems (Ampim et al., 2010; Sloan et al., 2012; Harada et al., 2017).

Advancing Urban Ecology Through Constructed Ecosystems

Planning and design of constructed ecosystems could offer opportunities for advancing the "ecology of cities" which is the science of coupled human-natural systems in the urban environment (Grimm et al., 2000; Pickett et al., 2001; McPhearson et al., 2016). In green infrastructure projects, design strategies intended to assure specific ecological processes and environmental goals often lack evidence. For example, green roofs and rooftop agriculture intended to reduce the nutrient load in runoff may in fact increase the load due to fertilizer application, because the present state of knowledge and technology are insufficient to allow precision nutrient management (Driscoll et al., 2015; Harada et al., 2018a). Socio-ecological assumptions are often implicit in constructed ecosystems, which could drive interdisciplinary studies of feedback loops between society, science, and transformation of the urban environments (Tanner et al., 2014; McPhearson et al., 2016). "Adaptive experiments" or "designed experiments" are among the approaches of embedding experiments and applying science to urban ecosystems by involving ecologists in design and management practices from the onset (Cook et al., 2004; Felson and Pickett, 2005; Kotsiris et al., 2013; Ntoulas et al., 2013a; Ahern et al., 2014). Constructed ecosystems are ideal for collaborative ecological research because components of constructed ecosystems such as plant selection, substrate properties, and drainage systems can be experimentally manipulated and replicated through design and management practices (Felson and Pickett, 2005; Felson et al., 2013). Design constraints could also be an advantage for experiments. For example, engineers are often constrained by abrupt hydrologic boundaries, shallow substrates, and centralized drainage systems because of budget limitations, regulations, professional guidelines, and load bearing capacity of buildings and underground structures. In such simple and discreet hydrological systems, inputs and drainage losses of water and nutrients can be studied most completely as in the forested catchments in the Hubbard Brook Long-Term Ecological Research (Likens, 2013). This approach would serve as a foundation for pursuing precise water and nutrient management in constructed ecosystems, which reduces the drainage loss of water and nutrients, while maintaining satisfactory crop yield and quality (Harada et al., 2017). Water and nutrient management is important for the practices of rooftop farming.

INTEGRATION OF ROOFTOP INTENSIVE AGRICULTURE IN URBAN ECOSYSTEMS

Rooftop Farming

Urban agriculture is a growing movement which aims to address the diverse goals of urban sustainability, including food security, food equity, efficient food supply chains, stormwater management, mitigation of urban heat island effects, and waste management using compostable waste (Brown and Jameton, 2000; Brown and Bailkey, 2002; Mougeot, 2006; Lovell, 2010; Lovell and Taylor, 2013; Ackerman et al., 2014; Russo et al., 2017). In economically developed countries, urban planning practices treated agriculture as a temporary activity for vacant lots before conversion to more profitable residential, commercial, and industrial land uses (Alonso, 1964; Van Veenhuizen and Danso, 2007). However, urban agriculture is becoming a long-term enterprise by increasing and stabilizing profits through (1) intensive production of fresh and perishable vegetables that have high long distance transportation costs from rural farms; (2) unique marketing strategies such as organic cultivation and production of heirloom and exotic varieties; (3) diversifying crop selection, and/or (4) incorporating non-cropping services such as tourism, environmental education, green job training, culinary events, nature therapy, and creation of lively neighborhood (van der Schans and Wiskerke, 2012; Plakias, 2016; Pölling et al., 2016, 2017).

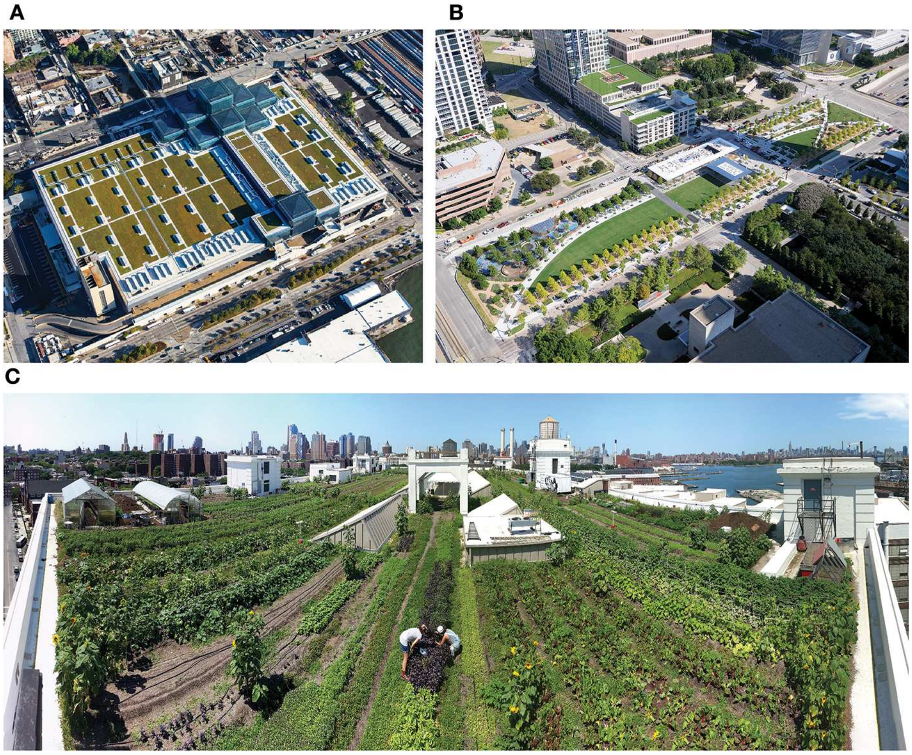

FIGURE 1 | Examples of constructed ecosystems on built surfaces. **(A)** A 2.7-hectare green roof growing drought-tolerant sedum species on the Javits Center in New York City, New York (Image © Javits Center). **(B)** Klyde Warren Park: a 2.1-hectar public park, growing trees, shrubs, lawns, and ornamental herbs on the capping structure over Woodall Rodgers Freeway in Dallas, Texas (Image © OJB Landscape Architecture). **(C)** The Brooklyn Grange: a 0.6-hectar rooftop farm growing vegetables on top of an 11-story building in the former Brooklyn Navy Yard in New York City, New York.

Limited space and competitive real-estate markets are impediments for in-ground agriculture, while farms retrofitted to roofs occupy otherwise underutilized space in the built environment (Specht et al., 2014; Thomaier et al., 2015; Whittinghill and Starry, 2016). New York City alone has 15,482 ha of rooftop surface, equal to 445 times the size of existing community gardens (Ackerman et al., 2013). Converting even a small portion of this space to agriculture presents important opportunities for advancing urban agriculture.

In addition to private investments, rooftop farming can combine policy supports and public funding from green building and green infrastructure initiatives. Since 2011, for example, Community-Based Green Infrastructure Program of NYC Department of Environmental Protection provides grants for construction of green infrastructure projects including rooftop farms as a part of 20-year green infrastructure masterplan (NYC DEP, 2010, 2011), while since 2013, NYC's new zoning code, "Zone Green," allows modification of buildings for enhancing urban sustainability, including the construction of rooftop farms (NYC DCP, 2012). One of the outcomes is the Brooklyn Grange, a 0.6 ha intensive vegetable production farm atop an 11-story building in the former Brooklyn Navy Yard, NYC (**Figure 1C**). The Brooklyn Grange yields 11,000-13,000 metric tons year^{-1} of organic vegetables, while expanding relationships with local residents, schools, restaurant owners, and non-profit organizations through vegetable sales, green job training, environmental education, and waste collection for composting (Plakias, 2016; Harada et al., 2018a).

Rooftop farming could enjoy further opportunities through the NYC's new green building policy known as "Climate Mobilization Act," which takes effect in 2024, mandating improvements in building energy performance including vegetated roofs (New York City Council, 2019). However, the scientific community has little hard data on the environmental and economic performance of rooftop farming. Empirical studies of water and nutrient budgets for operational rooftop farms could serve as a starting point for understanding and improving the performance of rooftop farming.

Hypothetical City-Scale Effects

Among the studies of rooftop farming using experimental systems, city-scale production capacity of rooftop farming was estimated only once (Orsini et al., 2014). They report that outdoor hydroponic systems (57% of site area) and planters using synthetic substrates (43% of site area) could maximize the yield of lettuce (*Lactuca sativa* L.), black cabbage (*Brassica oleracea* Acephala Group), chicory (*Cichorium intybus* L.), tomato (*Solanum lycopersicum* L.), eggplant (*Solanum melongena* L.), chili pepper (*Capsicum annum* L.), cantaloupe (*Cucumis melo* L.), and watermelon (*Citrullus lanatus* Thumb.) in the flat

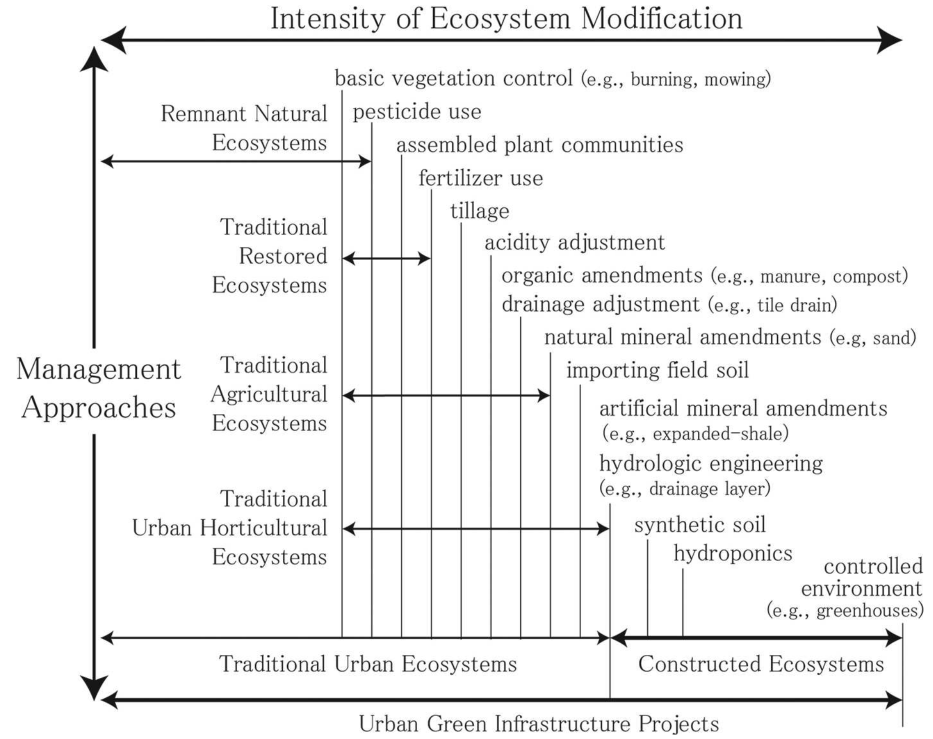

FIGURE 2 | Types of Urban Ecosystems and Intensity of Ecosystem Modification. (adapted from Figure 2 in Sloan et al., 2012).

roof areas (82 ha) of Bologna, Italy, thereby providing 77% of the city's fresh vegetable demand (16,169 metric tons year^{-1}). The study did not estimate city-scale environmental impacts, such as potable water consumption for irrigation, fertilizer input, and drainage loss of water and nutrients (Orsini et al., 2014). Although measurements from experimental systems provide useful insights for understanding the performance of rooftop farming, it is important to study operational rooftop farms because efficiency of water and nutrient management is often higher in small-scale well-managed experimental plots than that in operational farms (see Cassman et al., 2002).

Among the studies of operational rooftop farms, only Harada et al. (2018a,b) report the budget of water and nitrogen of the Brooklyn Grange Navy Yard Farm in NYC, which can be used for estimating the city-scale effect of rooftop farming as summarized in **Supplementary Table S1, S2**. If all suitable rooftops in NYC (1,246 ha) were occupied by rooftop farms like the Brooklyn Grange, the city-scale potable water consumption and nitrogen discharge from wastewater treatment plants to surface water could increase by 0.3 and 0.6%, respectively, while producing 27,344 metric tons year^{-1} of fresh vegetables, equivalent to fresh vegetable consumption of 3.8×10^5 people, or 4% of the estimated city-scale vegetable consumption (**Supplementary Table S1, S2**). Leafy vegetables are one of the most important fresh vegetables grown in urban agriculture including rooftop farming (Ackerman et al., 2013; Baudoin et al., 2017; Harada et al., 2018a), and city-scale demand of greens mix (leafy lettuce and mustard greens) is largest among leafy vegetables grown at the Brooklyn Grange (**Supplementary Table S2**). If all cropped area were dedicated to mixed greens, then the city-scale rooftop farming could produce 38% of the NYC's demand (**Supplementary Table S2**).

Although the NYC's city-scale suitable rooftop area was 15 times of that in Orsini et al. (2014), fresh vegetable production was only 1.1 times of that in Orsini et al. (2014) due to the relatively low yield at the Brooklyn Grange. Average yield per unit are of the entire roof (including both cropped and uncropped areas) at the Brooklyn Grange is only 14% of that reported by Orsini et al. (2014) (15.2 kg m^{-2} year^{-1}), in part, because the growing season was longer (year-around) in Bologna than at the Brooklyn Grange (226 days). Also, the percentage of cropped area in the entire roof is smaller at the Brooklyn Grange (47%) than that reported by Orsini et al. (2014) (65%), while even when the uncropped area is excluded, the average yield at the Brooklyn Grange is only 20% of that reported by Orsini et al. (2014). Other factors for relatively low yield at the Brooklyn Grange include crop selection, design of the production system, and the less intensive management in larger operational farms than that in small experimental plots.

Biodiversity Conservation

Within the context of city-scale ecosystems, isolated patches of urban green space, including urban agriculture and green roofs, can be hotspots for biodiversity (Cook-Patton and Bauerle, 2012; Forman, 2014; Williams et al., 2014; Borysiak et al., 2017; Lepczyk et al., 2017). Declining wildlife populations in farmland and rural areas due to pesticide use increased the importance of cities as wildlife refuge, while organic cultivation in rooftop farming can increase plant, insect, and bird habitat in densely built environments and contribute to urban corridor networks (Gilbert, 1989; Chamberlain et al., 2000; Orsini et al., 2014; Bretzel et al., 2017; Dang, 2017; Hall et al., 2017). Insect pollinators are important indicators of biodiversity across land uses including urban environments, while beekeeping contributes directly to food production (Tommasi et al., 2004; Broadway, 2009; Plakias, 2016; Bretzel et al., 2017; Hall et al., 2017). Studies of green roofs report that management, plant selection, and substrate properties have strong influence on species composition and abundance for wild flora, birds, invertebrates, and the substrate microbial community, emphasizing the need of empirical studies specific to rooftop farming (Dunnett et al., 2008; Dvorak and Volder, 2010; Fernández Cañero and González Redondo, 2010; McGuire et al., 2013, 2015; Williams et al., 2014; MacIvor and Ksiazek, 2015; Bretzel et al., 2017; Ksiazek et al., 2018; Aloisio et al., 2019).

Stormwater Management

Estimated city-scale evapotranspiration (ET) summarized in **Supplementary Table S1** indicates that the potential of stormwater retention by rooftop farming, equals 2.3 X that of the urban forest in NYC. The Brooklyn Grange uses a synthetic substrate for growing vegetables, while the base material of the substrate is heat-expanded shale, which can increase drainage by lowering water-holding capacity of the substrate (Rowe et al., 2014; Ntoulas et al., 2015; Harada et al., 2018b). Although the Brooklyn Grange retained little stormwater during the growing seasons, it should be noted that precipitation exceeded ET at the Brooklyn Grange, which means that stormwater discharge and irrigation demands could be eliminated while maintaining satisfactory yield through enhanced water-holding capacity of the substrate and recirculating drainage (Harada et al., 2018b). Outdoor hydroponic systems can also be used for rooftop farming, which could eliminate drainage discharge by using closed-circuit systems for nutrient solution, and incorporating stormwater recycle systems (Orsini et al., 2014; Sanyé-Mengual et al., 2015b; Rodríguez-Delfín et al., 2017; Tsirogiannis et al., 2017). However, water management using electric pumps requires further research because pumps' electricity consumption can be the largest environmental cost of rooftop farming (Sanyé-Mengual et al., 2015b).

Rooftop Greenhouses

Another option for rooftop intensive agriculture is rooftop greenhouses which could achieve higher levels of yield, water use efficiency, and stormwater retention than those of rooftop farming. For example, Sanjuan-Delmás et al. (2018) report the tomato yield of 19.6 kg m^{-2} $year^{-1}$ in rooftop greenhouse in the city near Barcelona, Spain, which exceeds yields of rooftop farms (5.1–14.3 kg m^{-2} $year^{-1}$) (Orsini et al., 2014; Grard et al., 2015; Harada et al., 2018a; Boneta et al., 2019). Rainwater was collected from roofs of the greenhouse and adjacent building, contributing to 80–90% of total water supply. While nutrient discharge exceeded that of a conventional greenhouse, this could be reduced by using a closed-circuit hydroponic system (Sanjuan-Delmás et al., 2018).

However, construction costs for rooftop greenhouse (299–764 USD m^{-2}) can be higher than those for commercial rooftop farming (54–150 USD m^{-2}) (calculated as 1 Euro = 1.12 USD) (Mandel, 2013; Sanyé-Mengual et al., 2015a; Proksch, 2016). Furthermore, it could be a challenge for rooftop greenhouses to compete with conventional greenhouses in terms of economic and environmental returns. For example, Sanyé-Mengual et al. (2015a) estimated that life-cycle production cost of rooftop greenhouses for tomato is 2.8 times that of conventional greenhouse (a steel-framed high tunnel with vertical sidewalls), requiring yield of 55 kg m^{-2} $year^{-1}$ for rooftop greenhouses to achieve higher economic and environmental returns than those of conventional greenhouse in Barcelona, Spain.

In terms of life-cycle costs of vegetable production, greenhouse cropping systems could be superior to outdoor agriculture in arid and cold regions that have high irrigation demands and short growing seasons, while life-cycle costs specific to rooftop greenhouses highly depend on regional economy, design, microclimate, and distance to major agricultural areas, which require further research (Cuéllar and Webber, 2010; Barbosa et al., 2015; Sanyé-Mengual et al., 2015a; Van Ginkel et al., 2017). While providing opportunities for sustainable food production, rooftop greenhouses do not contribute to habitat creation and environmental education relevant to wildlife biodiversity.

CONCLUSIONS

Constructed urban ecosystems can be different from traditional subjects of ecology in terms of environmental and economic performance, but they are direct outcomes of urban planning and design intentions, which are important and testable subjects for understanding and improving coupled human-natural systems. Among those constructed ecosystems are rooftop intensive vegetable production systems aiming to achieve diverse goals of sustainability within the practices of urban green infrastructure projects, while the scientific community has little information for instructing and navigating urban planning and design. Future research could be motivated by the following questions:

(1) What are the optimal levels of yield, water and nutrient use efficiency, and stormwater management for balancing environmental and economic costs of rooftop intensive agriculture?
(2) How do economic and environmental returns of rooftop intensive agriculture differ in specific system design, climate zone, regional economy, and distance to major agricultural areas?
(3) What are the specific contributions of rooftop farming to enhancing urban biodiversity?
(4) What are the best ways of involving scientists and designing experiments in rooftop intensive agriculture for understanding and improving social ecological systems?
(5) How could urban planning and design integrate different options of rooftop intensive agriculture

and other green spaces for achieving diverse goals of urban sustainability?

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

YH: experimental design, sample collection, sample analyses, data analyses, and manuscript preparation. TW: experimental design and manuscript preparation.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2020.00076/full#supplementary-material

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