Linking Urban Land Use to Aquatic Metabolic Regimes

by

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April 2021

Master's project submitted in partial fulfillment of the
requirements for the Master of Environmental Management degree in
the Nicholas School of the Environment of
Duke University

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1. EXECUTIVE SUMMARY

Metabolism is a foundational property of ecosystems, and the productivity of rivers determines their capacity to retain and transform nutrients as well as support biodiversity. Stream metabolism has been increasingly used to assess waterway health due to its relevance across sizes and types of streams, sensitivity to stressors, and ability to be measured continuously. Land use change can affect metabolism through numerous mechanisms, including hydrology, light regimes, and nutrients, which may respond to changes in land use at different scales. This study used existing high frequency metabolism records and geospatial data to examine relationships among measures of catchment and riparian condition and stream Gross Primary Production (GPP). The primary goals were to identify the mechanisms by which urbanization and land use change affect metabolism, the scales at which these drivers exert the most influence, and any variance present across regions. Quantifiable proxies for each mechanism were used to characterize and assess its effect on GPP response along an urban land use gradient and spatial scale.

This study focused on small headwater streams located in mesic environments. The study area for this project included a collection of stream gage sites in the eastern United States, each of which is located east of 96 degrees west longitude and has a total catchment area of less than 26 square kilometers or less. Four primary regions of focus were selected based on their display of a complete urban gradient (low total percent urban area to high total percent urban area within the catchment) among stream gage sites: Atlanta metropolitan area, Kansas City metropolitan area, Mid-Atlantic region, and Washington D.C. metropolitan area.

Overall, we found that whole watershed scale urban cover was weakly correlated with stream characteristics that affect metabolism. Total percent tree canopy cover appears to exert control over metabolism at the local reach scale, while total percent urban land cover, total percent imperviousness, and total road density do this at the whole watershed scale. In all cases, GPP was negligible above a threshold land cover, and the higher variance in GPP at low to moderate urbanization levels is controlled by local canopy. This suggests that metabolic regimes arise from processes at multiple scales. Differences in GPP among the four focal regions are likely due to differences in climate, impervious surface, and riparian canopy among urban areas.

These findings suggest that effective interventions may require catchment scale efforts to preserve and restore hydrologic regimes as well as local interventions to improve riparian condition. This has implications for resource protection, mitigation, and future planning. Understanding the relative importance of these processes and the scales at which they affect streams is critical for environmental management decisions, including the conservation and rehabilitation of streams, as well as designing appropriate interventions. Ultimately, this project demonstrates how richer and larger datasets can expand our understanding and inform decision making at new scales. Future temporal scale analyses that assess the seasonality or disturbance recovery trajectories of these data may further benefit our understanding of these processes and relationships. Additionally, we suggest conducting comparative analyses of these data in terms of seasonal patterns and how temporal patterns differ between GPP and ER.

2. INTRODUCTION

Ecosystem metabolism refers to the cumulative production and consumption of organic material by organisms in an ecosystem (Odum 1956). In rivers and streams, plant and algae inhabitants may generate organic material. In addition, organic material may be transported directly to a river or stream as detritus or carried indirectly by inflow in dissolved forms. Photosynthesis and decomposition are manifested through the processes of gross primary production (GPP) and ecosystem respiration (ER), respectively. GPP and ER produce temporal patterns in response to episodic and seasonal processes, which are referred to as metabolic regimes (Bernhardt et al. 2018).

Metabolism is a foundational property of ecosystems. Furthermore, stream productivity is one primary factor that determines their ability to retain and alter nutrients, as well as support biodiversity (Savoy et al. 2019). Stream metabolism has emerged as a method by which to assess waterway health, as it is responsive to land use variation (Clapcott et al. 2016). Metabolism is a property that is applicable to all sizes and types of streams (Izagirre et al. 2008). Additionally, it can be continuously measured and is sensitive to stressors, including eutrophication and riparian cover changes (Izagirre et al. 2008). Thus, metabolism can help indicate stream function.

Many anthropogenic changes, especially land use, affect metabolism. Largely influenced by their position in the landscape, streams are impacted by factors that signify catchment urbanization, including stormwater, pollutants, and warming (Violin et al. 2011). Variance among metabolic regimes is observed across catchment land uses (Savoy et al. 2019). Land use change impacts the hydrologic, light, and nutrient regimes, via its direct effects on riparian canopy cover and impervious surfaces. This, in turn, affects stream metabolic rates. Increased urbanization leads to heightened hydrological flashiness (Reisinger et al. 2017), and flood flashiness effectively reduces metabolism rates (Qasem et al. 2019). In addition, the connectedness of impervious surfaces may be responsible for variation in the size of ecosystem degradation with respect to similar amounts of watershed development (Baruch et al. 2018).

Land use change affects metabolism in several different ways. These proximate controls are sensitive to catchment characteristics at different scales and likely to operate at such. How these mechanisms play out may differ depending on region or geographic location as well. Light exerts control on ecosystem metabolism rates in streams spanning large geographic areas (Mulholland et al. 2001). A relationship exists between average daily GPP, ER, the seasonality of stream metabolism, and land use intensity in which greater variability is observed with high land use stress (Clapcott et al. 2016). Stream metabolism has been observed to be more resistant to high flow events at larger scales (Uehlinger 2000). Also, turbidity, in part, controls primary production, as do activities that occur within a catchment. Consequently, GPP decreases with increased population density (Izagirre et al. 2008). Disentangling these controls on metabolism is difficult because they can operate through intermediary mechanisms such as turbidity, which is both sensitive to hydrologic regime and affects light. These are not mutually exclusive.

Understanding these different causal pathways and the scales at which they exert control is necessary to minimize the effects of land use change on stream metabolic function via resource protection, mitigation, and planning. Furthermore, this is imperative for appropriate and effective intervention and management—from the macro scale (regional and watershed planning) to smaller local interventions (local reach and riparian zone). An increase in available empirical data provides new opportunities to examine these relationships at new scales. The transition to large-scale science has the potential to heighten our ability to characterize the variation in metabolic regimes, as well as their drivers. Metabolic patterns, in turn, can be incorporated into stream condition assessments for management and policy (Palmer et al. 2012), and combining these types of observations with model predictions can leverage the value of data in management and promotes feedback between observation, understanding, and action (Hipsey et al. 2015).

Much of our current empirical understanding of these relationships comes from studies that are replicated within, but not across, urban environments and often from observations that are not continuous, which misses a rich temporal dynamic. Thus, we used existing data to perform our analyses. The primary goal of this project was to identify the mechanisms by which urbanization and land use change affect metabolism, the scales at which these drivers exert the most influence, and any variance in these outcomes across regions. Quantifiable proxies for each mechanism were used to characterize and assess their effect on GPP response along an urban land use gradient and spatial scale. More specifically, we aimed to characterize catchments geospatially, identify catchment land use as an indicator for riparian condition, and relate land use and riparian condition to stream productivity.

3. MATERIALS AND METHODS

3.1 Study Area

The study area for this project includes a collection of stream gage sites in the United States, each of which is located east of 96 degrees west longitude and has a total catchment area of less than 26 square kilometers. Thus, this project primarily examines small headwater streams in predominately mesic environments. Four primary regions of focus were selected for assessment based on their display of a complete urban gradient (low total percent urban area within the riparian buffer to high total percent urban area within the riparian buffer) among stream gage sites: Atlanta metropolitan area, Kansas City metropolitan area, Mid-Atlantic region, and Washington D.C. metropolitan area (Figure 1).

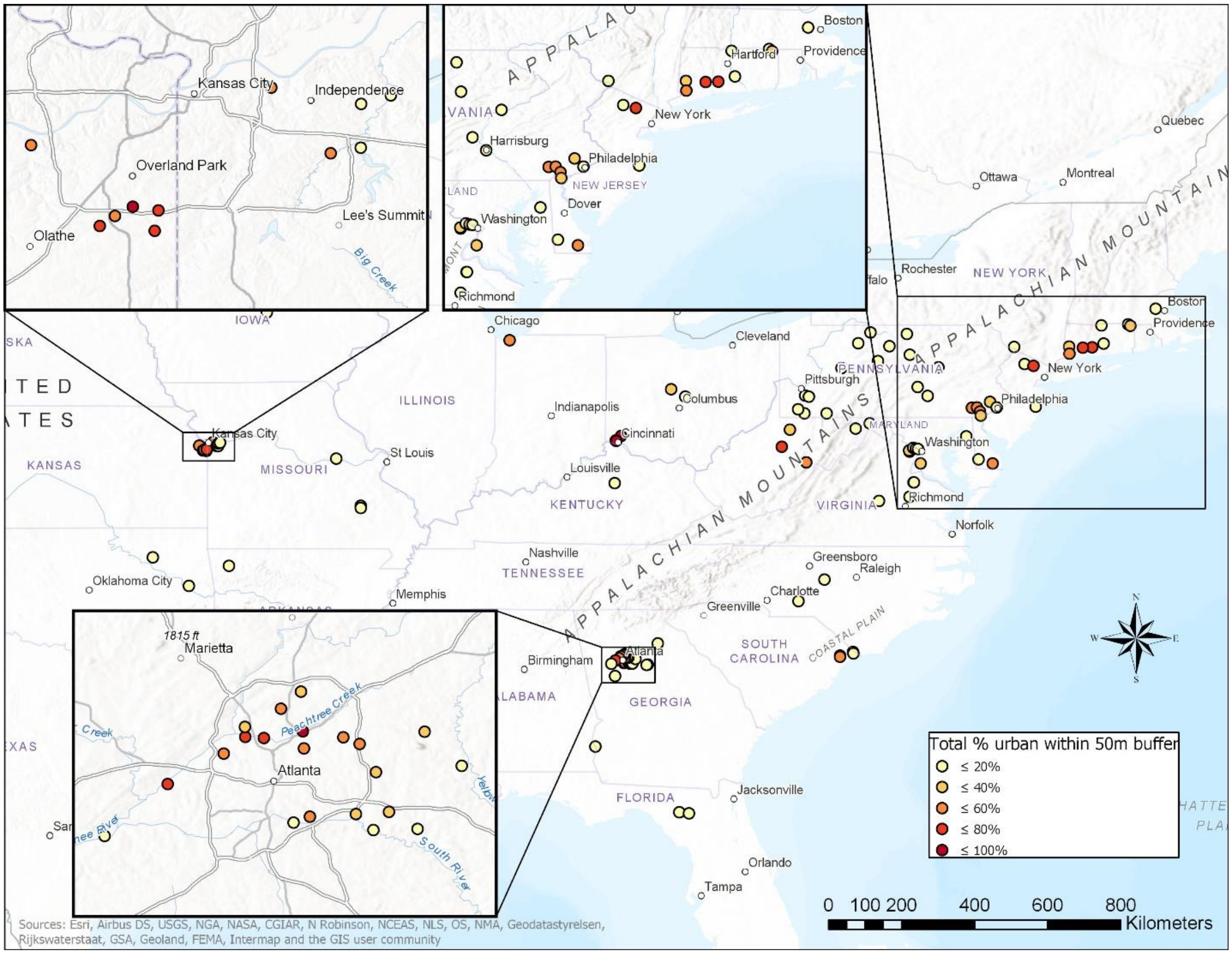

Figure 1. Map of study area and stream gage sites located within it. Each stream gage site is colored based on the urban fraction present within a 50m riparian buffer of its respective stream.

3.2 Data Sources

The site data used in this study was sourced from the U.S. Geological Survey (USGS) and the StreamPULSE dataset. The USGS data used was gage site data indexed to the National Hydrography Dataset (NHD), and the StreamPULSE data included location and corresponding

USGS gage ID information for sites. Site attribute and characteristic data were sourced from the NHDPlus Version 2.1.

This analysis links time series of metabolic activity, specifically GPP, in streams draining catchments with varied urban land uses. The data used included metabolism and catchment characteristic data. Metabolism data primarily came from the Appling et al. 2018 dataset, *Metabolism Estimates for 356 U.S. Rivers*. This stream metabolism data consisted of daily estimates of GPP. Catchment characteristic data was derived from several sources. The catchment data include catchment basin area, as well as land use mechanism proxies pertaining specifically to the light regime and hydrologic regime. Catchment basin area data was sourced from the NHDPlus Version 2.1 dataset. Land use mechanism data pertaining to the light regime, including total percent tree canopy cover within a 100m buffer of each stream, was also sourced from the NHDPlus Version 2.1 dataset. Similarly, land use mechanism data pertaining to the hydrologic regime included measures of urbanization such as total percent imperviousness and total road density, which came from the NHDPlus Version 2.1 dataset. Land cover data were obtained through the NHDPlus Version 2.1 dataset as well, which draws from the 2011 National Land Cover Database (NLCD). For this project, the sum of NLCD classes 21-24 (urban land cover classes) was calculated to determine the total percent urban land cover for each site's watershed.

3.3 Data Compilation and Analysis

RStudio software was used to compile, synthesize, and analyze these data. Site and land use characteristic data from separate USGS, NHDPlus, and StreamPULSE datasets were joined using tivyverse packages based on the USGS gage ID, NHDPlus ID, and National Water Information System (NWIS) ID information shared by multiple datasets. Once a final combined dataset had been produced, it was filtered to only include stream sites located east of 96 degrees west longitude with a catchment area of less than 26 square kilometers.

Land use change affects the light, hydrologic, and nutrient regimes, which, in turn, impact metabolism (Figure 2). Our analyses focused on land use mechanisms of the light and hydrologic regimes. Quantifiable proxies for each mechanism were used to characterize and assess their effect on GPP response along an urban land use gradient and spatial scale. Total percent tree canopy cover was used as a proxy for the light regime, while total percent urban land cover, total percent imperviousness, and total road density were used as urbanization proxies of the hydrologic regime.

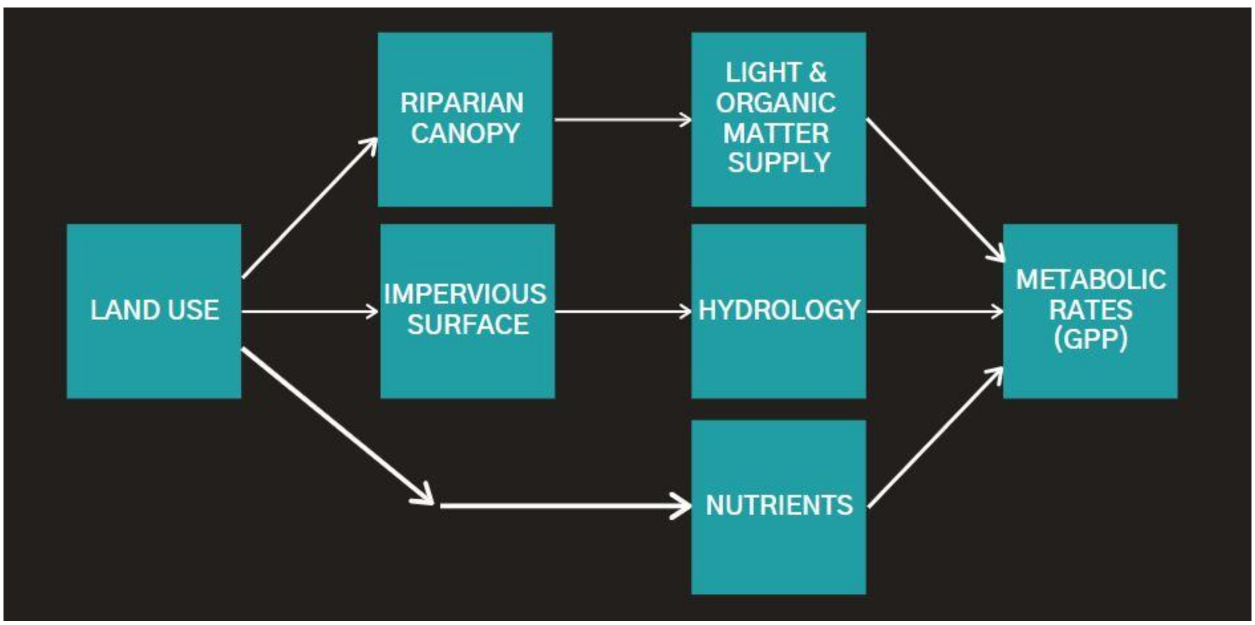

Figure 2. Causal pathways diagram showing the relationship between land use and the hydrologic, light, and nutrient regimes and, ultimately, metabolism.

Analyses aimed to address three primary questions: What are the mechanisms by which urbanization and land use change affect metabolism? At what scales do these drivers of metabolism exert the most influence? How do these outcomes vary across regions? First, catchments were characterized geospatially with respect to the distribution of impervious and urban land cover within them. Then, as a means to help identify catchment land use as an indicator for riparian condition, Pearson's correlations were performed on the proxies of the light and hydrologic regimes, and plots were generated from comparative analyses. Lastly, urban land use and riparian condition were related to stream productivity by performing Pearson's correlations on the proxies of the light and hydrologic regimes with respect to GPP, and these proxies were plotted in comparison to GPP.

The scales at which the proxies of the light and hydrologic regimes were analyzed included the local reach scale and the whole watershed scale. For simplicity, the local reach scale and the whole watershed scale are referred to as CAT and TOT, respectively, in our analyses. Total percent tree canopy cover was primarily analyzed within the upstream riparian area (a 100m buffer) of the local reach scale, while total percent urban land cover, total percent imperviousness, and total road density were analyzed at the whole watershed scale. The scales at which primary analyses were performed were reflective of the scales at which each metric exerted the most influence on GPP.

4. RESULTS

4.1 Interrelationship Among Urbanization Variables

A Pearson's correlation was run on each of the urban variables of interest—total percent urban land cover, total percent imperviousness, and total road density—to assess their relationship with one another (Figure 3). Of these, the relationship between total percent urban land cover and total road density is the strongest with a correlation value of 0.98, followed by the relationship between total percent urban land cover and total percent imperviousness, for which the correlation value is 0.96. The relationship between total percent imperviousness and total road density has a correlation value of 0.91. Each of these relationships is strong, thus indicating the positive relationship between these three measures of urbanization is substantial, and these metrics are closely related. Therefore, each urbanization metric is likely to exert a similar influence on GPP.

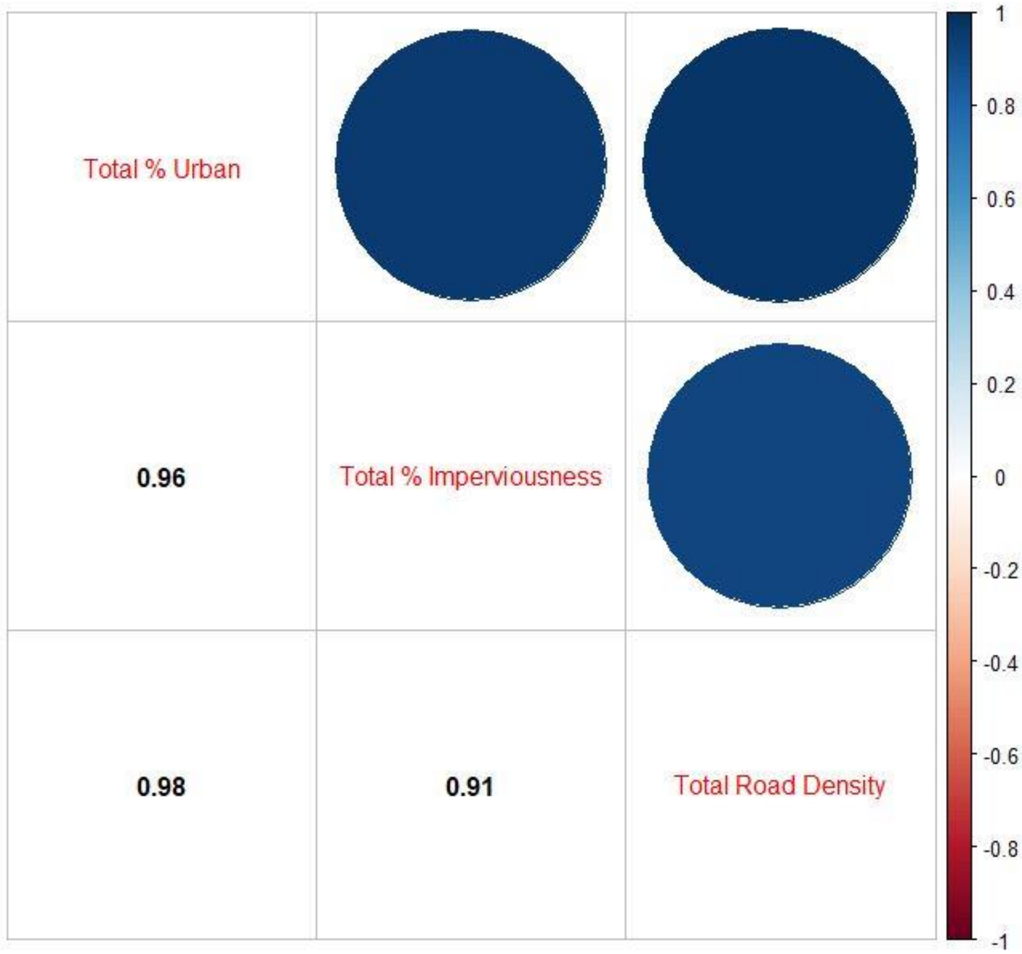

Figure 3. Correlation plot showing the strength and type of relationship between urbanization variables.

4.2 Scales of GPP Predictors

The temporal pattern of GPP in the eastern United States and other temperate areas is complex. In these areas, there is often a sizeable peak in GPP observed in the spring and sometimes a small peak in the fall. In the following plots generated from our analyses, the observed variance in GPP data points along the y-axis is representative of the temporal dynamic (seasonality) of the data, but is collapsed to one dimension. When total percent urban land cover (Figure 4), total percent imperviousness (Figure 5), and total road density (Figure 6) are plotted against GPP, a trend toward lower production in areas of high urbanization is observed. In addition, we found that whole watershed scale urban cover is moderately correlated with mean GPP (Pearson's correlation value = -0.31). Other measures of urbanization are also moderately to weakly correlated with average GPP, as the Pearson's correlation values for total percent imperviousness and total road density are -0.28 and -0.29, respectively.

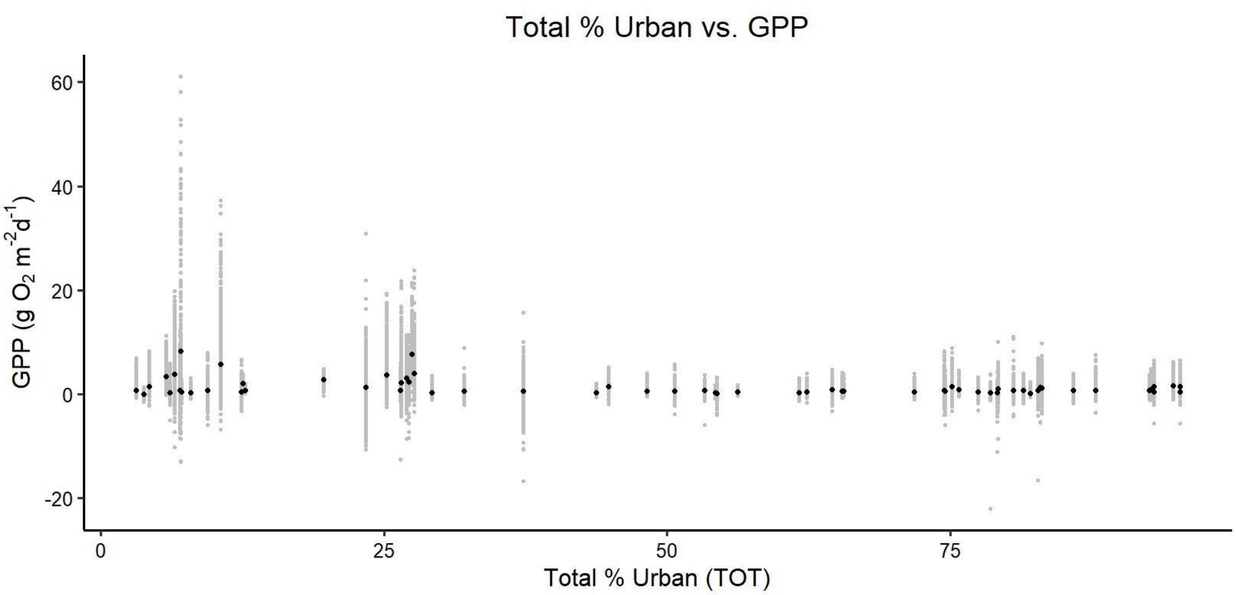

Figure 4. This plot shows continuous GPP values for each stream within the four focal regions of our study (gray points) with respect to the total percent urban land cover at the whole watershed scale. The black points represent the mean GPP values for each stream reach.

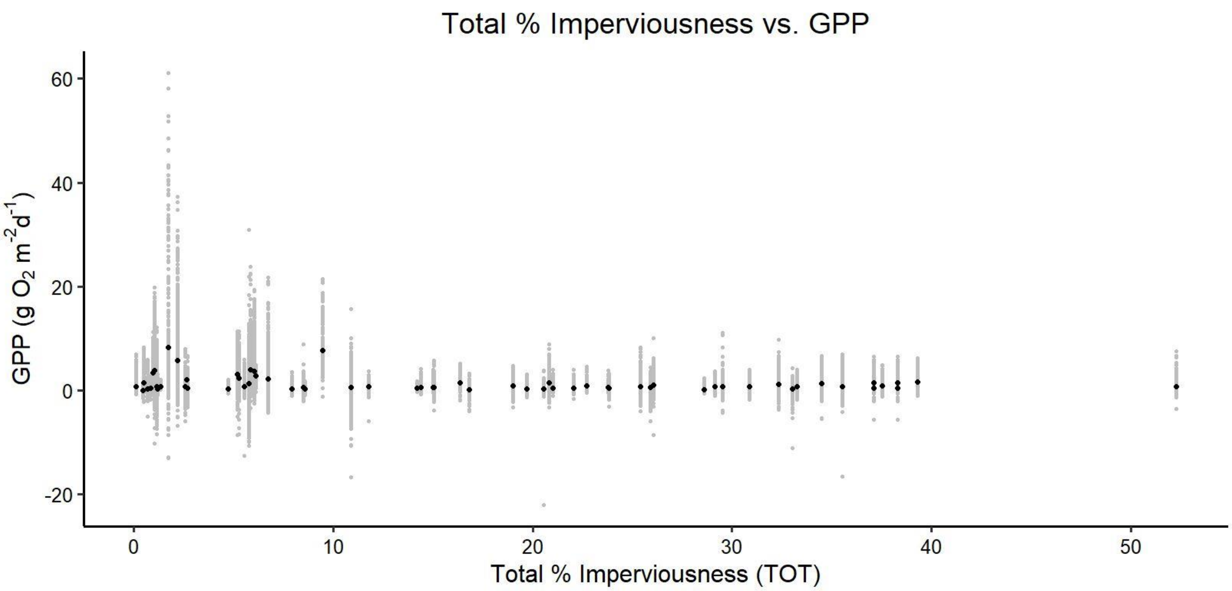

Figure 5. This plot shows continuous GPP values for each stream within the four focal regions of our study (gray points) with respect to the total percent imperviousness at the whole watershed scale. The black points represent the mean GPP values for each stream reach.

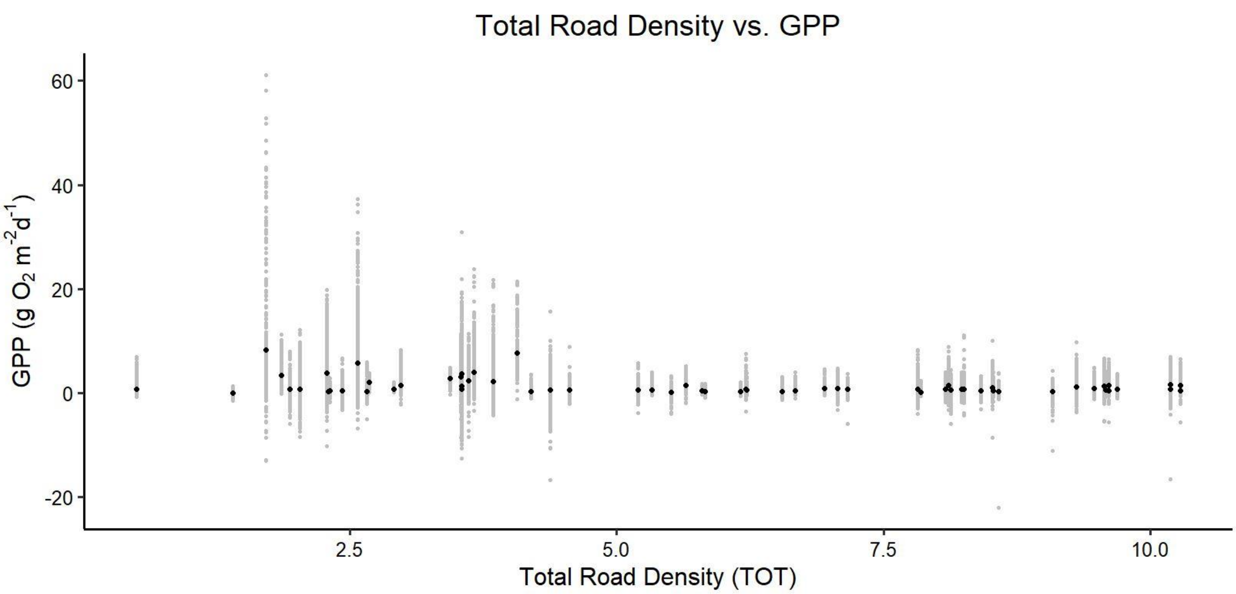

Figure 6. This plot shows continuous GPP values for each stream within the four focal regions of our study (gray points) with respect to the total road density at the whole watershed scale. The black points represent the mean GPP values for each reach.

When total percent tree canopy cover is plotted against GPP (Figure 7), a trend toward lower production in areas of greater canopy cover is observed. Total percent canopy cover within a 100m buffer of each stream was found to be moderately correlated with average GPP (Pearson's correlation value = -0.45), though it displayed a stronger relationship than any of the assessed urbanization variables. Each of these proximate variables, measures of both riparian canopy and urbanization, best predicted metabolism at different scales. Total percent urban canopy cover, total percent imperviousness, and total road density exerted the most influence on GPP at the whole watershed scale (Figures 4-6), while total percent canopy cover within a 100m buffer of a stream best predicted GPP at the local reach scale (Figure 7).

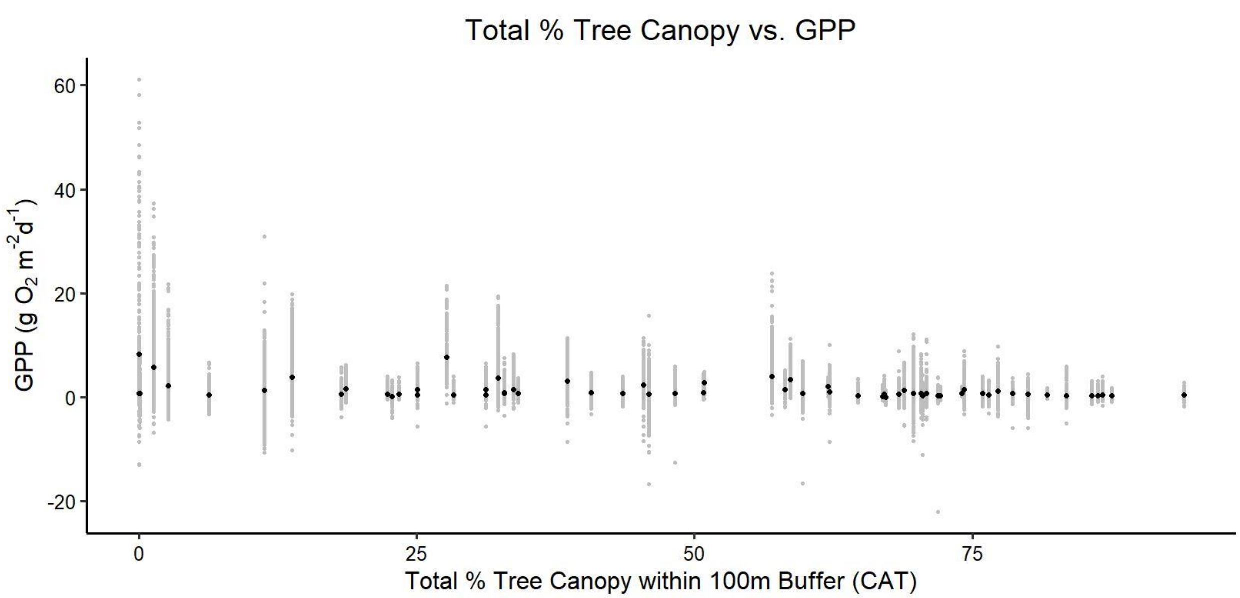

Figure 7. This plot shows continuous GPP values for each stream within the four focal regions of our study (gray points) with respect to the total percent tree canopy cover within a 100m riparian buffer. The black points represent the mean GPP values for each stream reach.

4.3 Interactive Effect on GPP by Urban Fraction and Riparian Canopy

A relationship between riparian canopy and urbanization is observed. At high amounts of urban land cover, GPP is low, while at low to moderate levels of urban land cover, we see the effective canopy (Figure 8). At a particular fraction of urbanization, high productivity is not observed. However, at low to moderate urbanization, productivity outcomes are largely varied. The trend observed is likely an effect of hydrology and impervious surface runoff, and the large variance in GPP at low to moderate levels of urbanization appears to be controlled, at least in part, by local canopy cover.

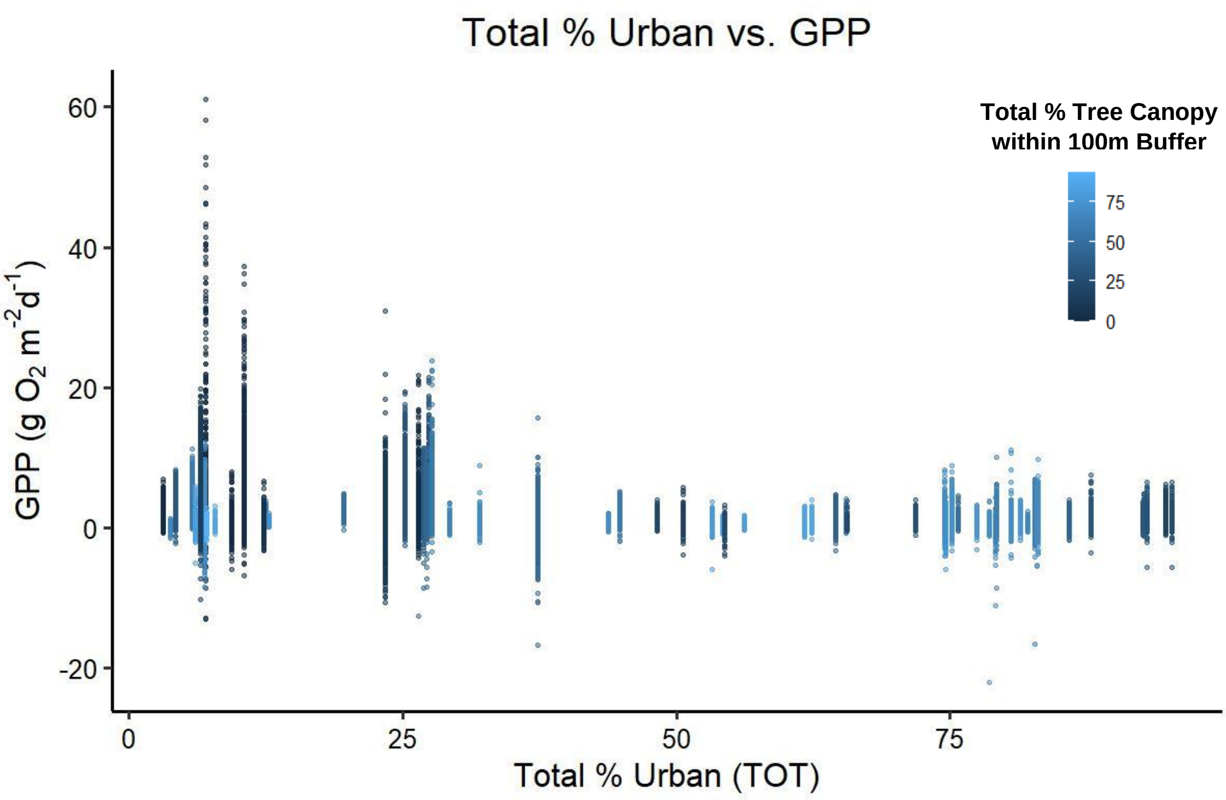

Figure 8. This plot shows continuous GPP values for each stream within the four focal regions of our study with respect to the total percent urban land cover. The points are colored based on the total percent tree canopy cover within a 100m riparian buffer of each stream.

4.4 Differences Among Regions in Urban Variables and Metabolism

Differences in urbanization variables and metabolism are present among regions (Figures 9-11). The study systems in these four focal regions are not distributed in the same way along these axes. The regions are clustered and structured along this urban gradient as a function of each urbanization metric: total percent urban cover (Figure 9), total percent imperviousness (Figure 10), and total road density (Figure 11).

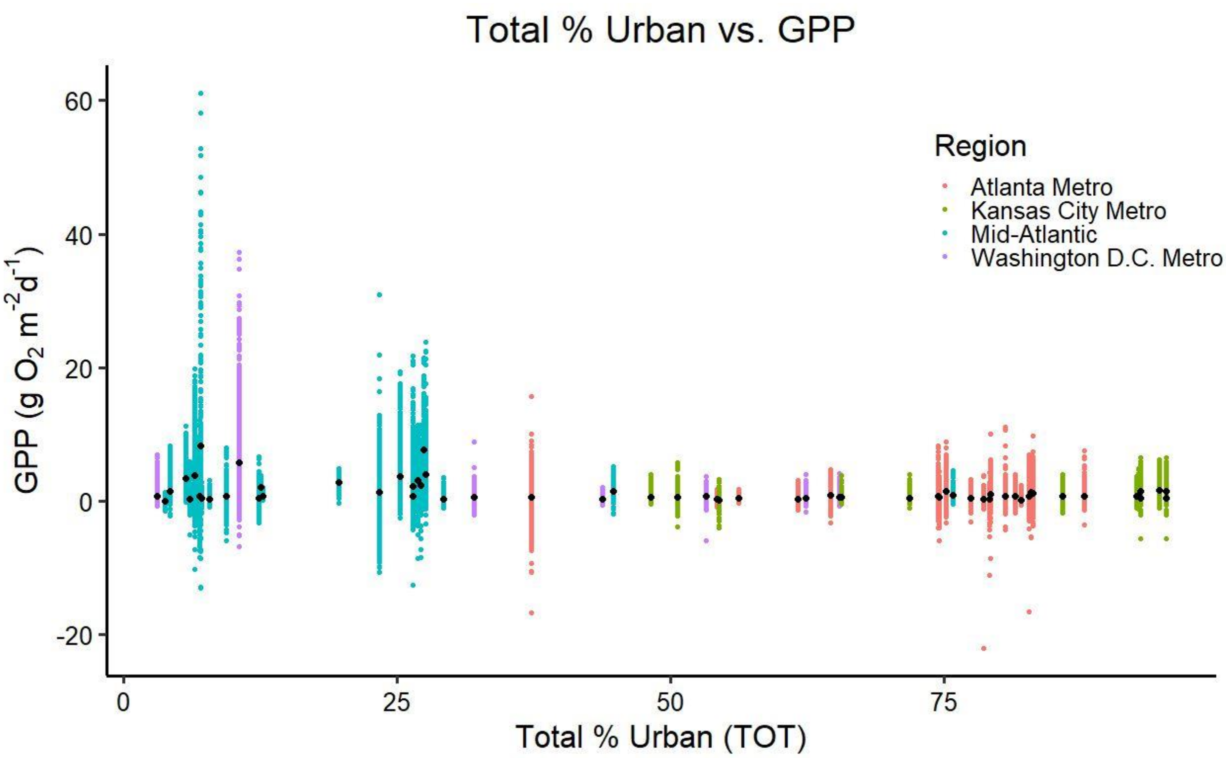

Figure 9. This plot shows continuous GPP values for each stream within the four focal regions of our study (colored points) with respect to the total percent urban land cover at the whole watershed scale. The black points represent the mean GPP values for each stream reach. Continuous GPP points are colored based on the region in which the stream they represent is located.

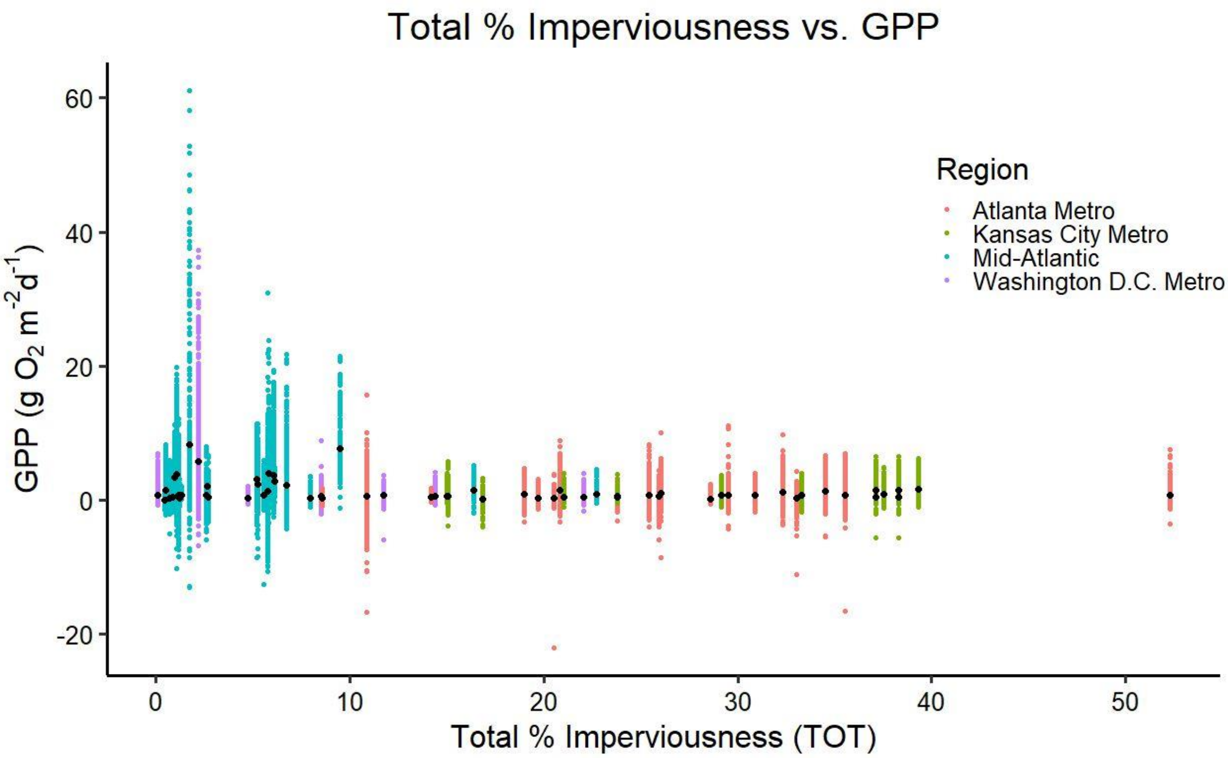

Figure 10. This plot shows continuous GPP values for each stream within the four focal regions of our study (colored points) with respect to the total percent imperviousness at the whole watershed scale. The black points represent the mean GPP values for each stream reach. Continuous GPP points are colored based on the region in which the stream they represent is located.

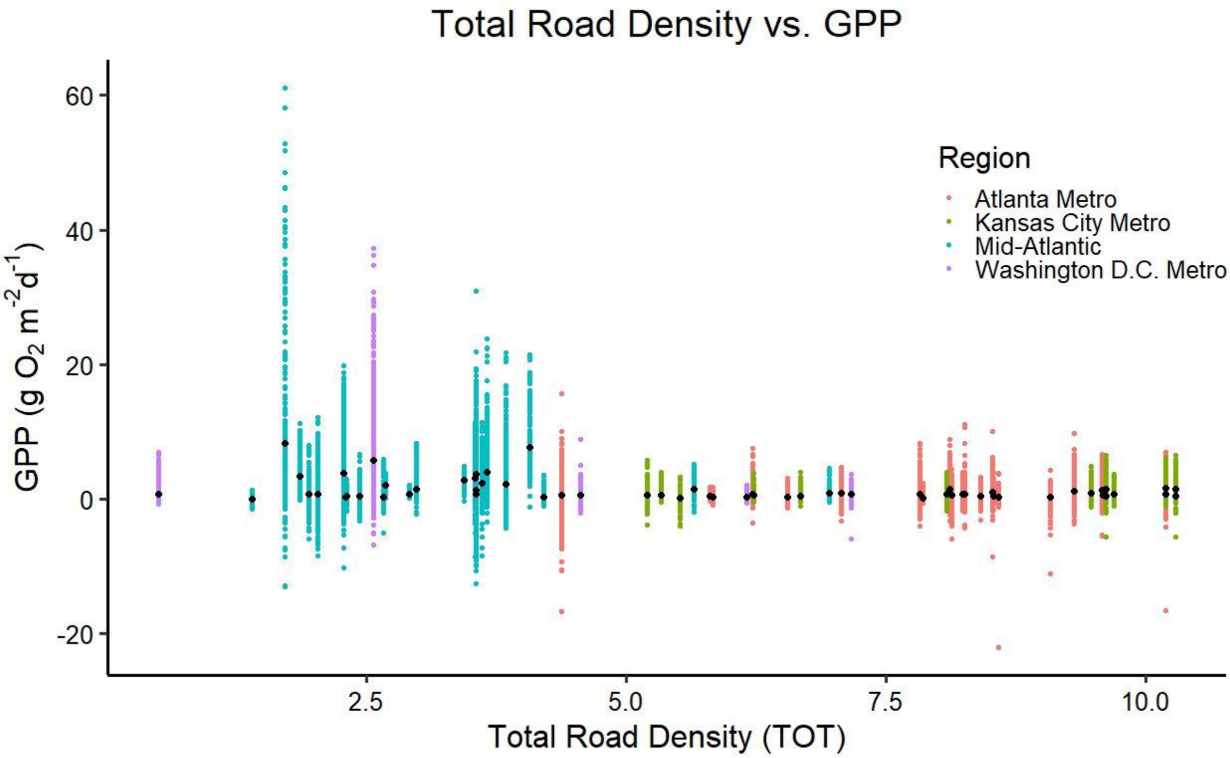

Figure 11. This plot shows continuous GPP values for each stream within the four focal regions of our study (colored points) with respect to the total road density at the whole watershed scale. The black points represent the mean GPP values for each stream reach. Continuous GPP points are colored based on the region in which the stream they represent is located.

Similar to urban fraction, total percent tree canopy cover appears to be structured regionally, and differences in GPP are apparent among the four focal regions (Figure 12). This may be due to the differences in canopy between each region, but may also not be able to explain all variance, as canopy structure differs among regions as well.

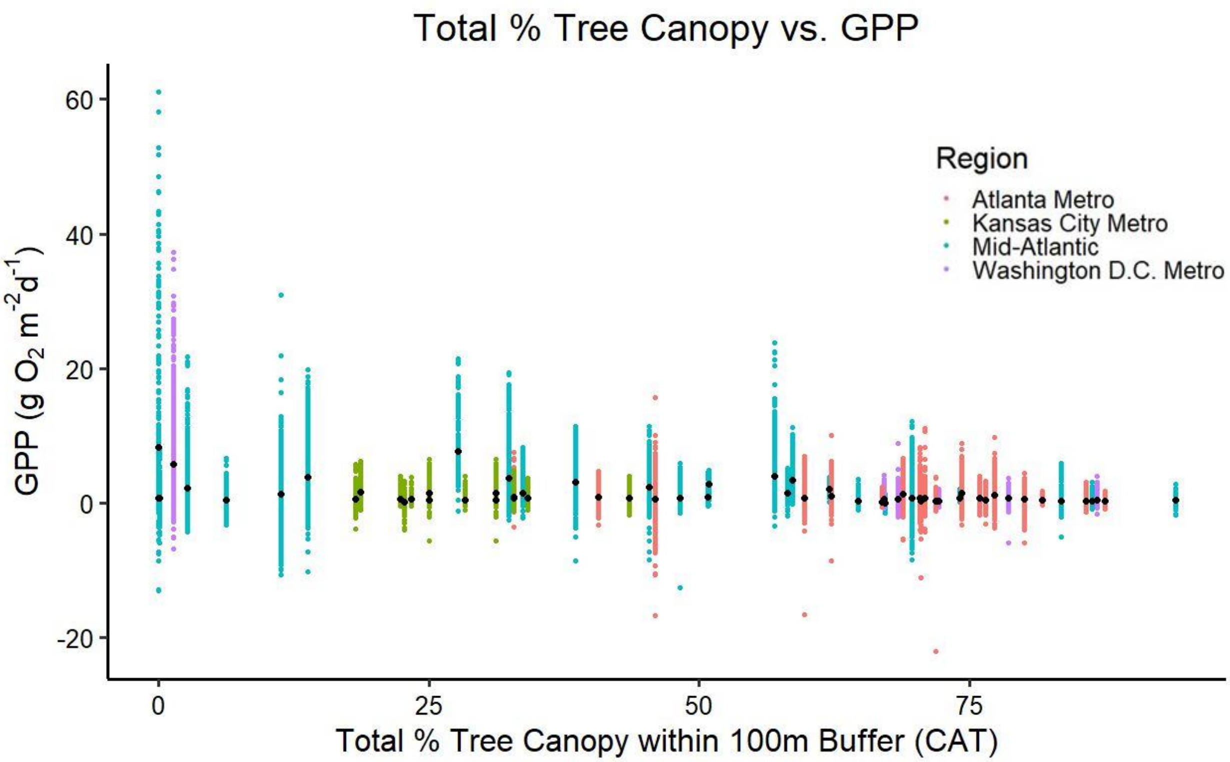

Figure 12. This plot shows continuous GPP values for each stream within the four focal regions of our study (colored points) with respect to the total percent tree canopy cover within a 100m riparian buffer. The black points represent the mean GPP values for each stream reach. Continuous GPP points are colored based on the region in which the stream they represent is located.

5. DISCUSSION

5.1 Levels of Urbanization and Metabolism

Above a particular fraction of urbanization, high productivity is precluded. However, at low to moderate urbanization, there are largely varied productivity outcomes. Canopy is likely responsible for this, as there are both open and closed canopies represented by these largely varied productivity values at low to moderate levels of urbanization. The overall trend here is largely an effect of hydrologic disturbance and impervious surface runoff, and the higher variance in GPP at low to moderate urbanization levels is controlled by local canopy.

5.2 Urbanization and Metabolism: The Importance of Different Scales

Our objective in this study was to assess the relationships between various measures of urban land cover and stream metabolism. We found that whole watershed scale urban cover was moderately correlated with stream characteristics that affect metabolism. These more proximate variables best predicted metabolism at different scales.

The total percent urban fraction at the whole watershed scale is a good predictor of road density and percent imperviousness, but not riparian canopy. However, our results show that canopy has a very weak relationship with the watershed scale urban fraction. Urban fraction does not tell us much about local canopy, which is an important driver of metabolism. There is an effect of urban fraction on the riparian canopy cover, but it is relatively weak compared to the regional scale differences. The canopy fraction varies as a function of urban fraction, but only very weakly compared to the broader differences among the regions. Total percent tree canopy appears to be structured regionally. This suggests that the spatial extent of urbanization can have very small or very large effects on canopy. Urbanization and riparian canopy are decoupled.

Conversely, the effect of canopy cover on metabolism operates at the local reach scale, while the effects of urban land cover, imperviousness, and road density are apparent at the whole watershed scale. If there are, indeed, different processes that might control metabolism, including shading and flooding, it may be that canopy is appropriately measured at the relatively local, or reach, scale, but hydrology is more influenced by the total road density at the broader, or whole watershed, scale. Canopy cover appears to be more relevant relatively locally, while road density is more relevant at the whole watershed scale. The catchment is relatively small, and the hydrologic influence is manifested through the whole drainage network. However, as light does not move downstream because it is locally represented, it is reasonable for total percent tree canopy to be predictive at the local reach scale and total percent urban, total percent imperviousness, and total road density to be predictive at the broader spatial scale of the whole watershed. Urban fraction better organizes the data at the broader scale, while urban fraction data at the catchment scale is not as useful. This is due to the fact that the whole catchment contributes to the hydrologic regime, whereas only the riparian zone canopy contributes to the light regime. This suggests that metabolic regimes arise from processes at different scales, and different types of metabolic patterns are thus generated within and across areas. We see there are different scales at which these relationships operate, and these scales reflect the scales of the processes at which each variable affects metabolism.

5.3 Differences Among Regions in Urban Variables and Metabolism

Differences in GPP apparent among the four focal regions could arise from. This may be due to the differences in distributions of canopy in each region, but may not be the case, as canopy structure also differs among regions. Another factor that may be responsible for differentiating the regions with regards to GPP is the amount of impervious surface present and the way in which it is distributed (i.e. connectivity), which ultimately impact the hydrologic regime**.** The regions are sorted and clumped by total percent imperviousness. There is not much road density within the riparian buffer of the Mid-Atlantic and Washington D.C. Metro streams, yet they are relatively productive. In contrast, the Atlanta Metro and Kansas City Metro streams have more impervious surface within their riparian buffers, so they are likely experiencing more hydrologic flashiness and disturbance. Additionally, there is much more compressed variability in the

Washington D.C. Metro area, even at urban fractions where there is elevated productivity in other regions.

The fact that GPP at the Kansas City Metro sites remains consistently low across various amounts of tree canopy, urbanization, imperviousness, and road density suggests that another factor(s) is responsible for limiting productivity in this region. It is important to note that the Kansas City Metro streams, as measured by flow, are smaller than those present in the other regions of study. Thus, there may be kinds of hydrologic disturbance such as drying that occur in these streams that do not happen in other regions. It is possible that this may contribute to the observed GPP values for these streams appearing low relative to those of streams in other regions. Additionally, urbanization involves toxins and pharmaceuticals, among other substances, entering these urban streams that, if not unique to urban systems, are more ubiquitous in urban systems and may also impact these relationships and trends.

5.4 Implications for Management and Decision-Making

Understanding the relative importance of these processes and the scales at which they affect streams is critical for environmental management decisions, including the conservation and rehabilitation of streams. Achieving a deeper knowledge of the mechanisms by which land use change effects metabolism is imperative for designing appropriate interventions. This is all in service of supporting better decision making. For example, reducing impervious cover within close proximity to a stream may not be very helpful, as it is unlikely to affect connected impervious cover at the scale of whole watershed, which ultimately drives stream hydrology and, consequently, metabolism. Conversely, riparian condition is of utmost importance for a stream's light regime. This suggests that at least some aspects of stream metabolism can be affected by riparian interventions. Focusing on these approaches may provide a way to promote watershed development by establishing specific actions that can be performed. That said, it is imperative to recognize that local scale restoration projects in the stream channel itself will rarely suffice on their own in catchments that have been significantly altered, as the increase in storm waters, nutrients and contaminants often associated with sizeable changes to the landscape limit the structural and functional impacts possible via in-channel stream restoration (Bernhardt and Palmer 2011). Rather, it is essential to begin restoration in highly disturbed and developed catchments with efforts to slow and interrupt the hydrologic connectivity between the catchment and streams in order to minimize peak flows and improve water quality (Bernhardt and Palmer 2011). Subsequent interventions aimed at protecting healthy riparian vegetation are important (Bernhardt and Palmer 2011), but more drastic restoration actions may be required for conservation in the wake of climate change (Palmer and Ruhi 2019). Thus, it is likely most beneficial to consider interventions at both the local and broader spatial scales to maximize the potential for stream and species restoration as well as watershed development.

5.5 Limitations

These GPP time series are quite rich and, in this project, we essentially used mean values to perform our analyses. We might be able to learn more about these mechanisms and their relationships if the seasonality and disturbance recovery trajectories of these data were assessed on a more temporal scale. In addition, we might obtain different and useful information from conducting future studies that specifically examine ecosystem respiration (ER). We would suggest conducting comparative analyses of these data in terms of seasonal patterns and how temporal trends differ between GPP and ER.

6. CONCLUSION

Our assessment of small mesic watersheds in the eastern United States shows that both riparian canopy and measures of urbanization aid in predicting stream metabolism. Furthermore, these mechanisms exert influence at different scales. The best scale for predicting GPP from measures of urbanization, including urban land cover, imperviousness, and road density, is the whole watershed scale. In contrast, the most appropriate scale at which to predict GPP from canopy cover is at the local reach scale. In addition, there is regional structure to these patterns in both riparian canopy and measures of urbanization and how they relate to metabolism.

Metabolism could be, and might should be, a management goal or metric of condition. A simple first approximation is that urban land cover above a threshold fraction will inevitably constrain stream metabolism. The particular shape of the response to urbanization may vary among regions, but overall, we consistently find that, in intensely urban areas, productivity is suppressed in this mesic population of watersheds. There may be consistent patterns in metabolic responses in warmer or colder regions, dry landscapes. But the widespread availability of metabolism data allows us to conduct assessments at broader scales than have been done previously. Ultimately, this project is a primary example of how richer and larger datasets can help expand our understanding and inform decision making at new scales.

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