Roadside Vegetated Filter Strips to Simultaneously Lower Stormwater Pollution Loadings and Improve Economics of Biorefinery Feedstocks

Hisham El-Husseini[a,b], Amira N. Chowyuk[a,c], Richard R. Gustafson[a], Heidi L. Gough[a*], Renata Bura[a]

[a]University of Washington, School of Environmental and Forest Sciences, Biofuels and Bioproducts Laboratory, Box 352100, Seattle, WA 98195-2100, USA;
hisham11027@gmail.edu, amira.chowyuk@posteo.net, pulp@uw.edu, hgough@uw.edu, renatab@uw.edu

*Correspondence: Heidi L, Gough; hgough@uw.edu; 206-685-7865
[b] Present Address: Momentum; Sacramento, California, USA.
[c] Present Address: Clean Energy and Carbon Solutions; Silicon Vally, California, USA.

Abstract:

Roadside vegetated filters strips (VFSs) reduce roadway runoff pollution by intercepting stormwater and reducing pollutant loads. VFS maintenance and operating costs can be reduced by designing the VFSs to serve as sites for production of marketable biomass. This biomass can provide feedstock for the emerging bioeconomy producing renewable fuels and biobased chemicals and products. Economic evaluation is needed to quantify the benefit of combining VFS with bioenergy biomass production. This evaluation requires a place-based approach to quantify availability of land, transportation costs, and benefits to sensitive habitats. We evaluated roadside land, within the state right-of-way, in Western Washington, to determine the total area available for implementing VFSs. These data were then used to estimate the volume and cost, of biomass produced on the filter strips, and the resultant reduction in pollutants emitted through highway runoff. The analysis showed that up to 5,600 hectares were available for roadside VFSs that would be within transportation distance of the theoretical biorefinery location. This space could produce up to 97 dry Gg per year of poplar biomass. The resulting reduction in biorefinery feedstock cost was up to $24 per dry Mg compared to biomass from dedicated tree farms. The results showed that combining roadside poplar with traditional dedicated poplar feedstocks can reduce the feedstock cost of the biorefinery from $76 to $67 per Mg for a biorefinery processing 150 Gg biomass per year. Environmental impact analysis showed that within the study area half of urban roadways and one-third of rural roadways in highly sensitive aquatic areas were amenable to VFS. Construction of VFS in these amenable areas would reduce total loadings to sensitive aquatic areas in urban areas by 26% for TSS, copper, and zinc, and by 10% for phosphorus, and nitrogen and by 21% for lead. The impact for rural sensitive areas was even greater where the VFS had potential to reduce total loadings to sensitive aquatic areas by 38% for TSS, copper, and zinc, by 15% for phosphorus and nitrogen, and by 31% for lead. This research showed an approach combining geographic information system (GIS) mapping and economic analysis to document simultaneous evaluation of cost and environmental benefits when considering use of non-traditional land for bioenergy crop production.

Key Words: geospatial analysis, environmental analysis, short rotation woody crop, ecosystem services, transportation corridor

Highlights:

- Multi-layering GIS applied to identify land near sensitive habitats for vegetative filters.

- Modeling demonstrated that growing roadside poplar provides environmental protection.
- Economic modeling showed that the resulting poplar feedstock reduced costs for biofuel production.

1 Introduction

Vegetated filter strips provide a critical function for pollution protection from roadway runoff. Roadway runoff carries pollutants, metals, and nutrients (Winston and Hunt, 2017) that impair the health of road-side habitats (Barbosa and Fernandes, 2021; Kayhanian, et al., 2007). Highway runoff pollution is an environmental concern that transportation agencies are increasingly expected to address (Shokri, et al., 2021). Roadside vegetated filters strips (VFSs) reduce highway runoff pollution (Boger, et al., 2018) and sequester soil carbon (Bouchard, et al., 2013). An opportunity is missed when the VFS is viewed only as a treatment unit. Potential exists to use the valorization of VFS through growth of bioenergy crops (Pennington, et al., 2012), thus simultaneously treating stormwater while making lignocellulosic bioenergy more economically viable. For the valorization of VFS to be effective, not only must stormwater management be achieved, but the economics of the final product production must also be viable.

Although roadside VFSs provide a solution to reducing highway runoff pollution, installation and maintenance can be cost prohibitive. VFS are designed as slightly sloped roadside embankments that host vegetation that improve water quality by reducing flow velocity and improving soil infiltration (Barrett, et al., 2006; Winston, et al., 2017). They reliably remove TSS and total metal concentration of roadway runoff, with more variable removal of nutrients (Li, et al., 2008; Shokri, et al., 2021; Wu and Allan, 2018) and dissolved organic pollutants (Flanagan, et al., 2018). VFS are more economically viable when maintenance costs are offset by producing a marketable biomass. The potential for roadside biomass energy recovery through anaerobic digestion biogas production has been considered (Brown, et al., 2020; Van Meerbeek, et al., 2019). An alternative is production of liquid fuels in a biorefinery (Voinov, et al., 2015). For example, the economics of growing poplar trees as a biofuel crop in conjunction with wastewater treatment has been previously described (Chowyuk, et al., 2021). Given the large availability of roadside land area and access to major transportation routes, VFSs represent a potential feedstock producer for a biorefinery (Pennington, et al., 2012). Pennington et al determined that 11,182 acres (4,500 hectares) of non-traditional lands (including highway rights-of-ways) were available for biomass production on highway medians in Michigan and that 89,000 tons/year of switchgrass could be produced. Not included in Pennington et al. (2012) or Voinov et al. (2015) was the potential for improved economics when growing biomass as part of a VFS to simultaneously reduce runoff pollution.

The objectives of the current study were to assess the potential supply and cost of biomass feedstock produced on roadsides and to assess the efficacy of highway runoff pollution reduction through roadside VFSs. Geospatial information has long been valued as a management practice for estimating land use changes related to transportation corridors (Karimi and Liu, 2004). Here, we apply geospatial approaches to investigate the economic viability of highway runoff pollution reduction systems for bioenergy crop production. By applying the study to a theoretical biorefinery location (in Western Washington, USA), we demonstrate an approach that combined geospatial data from geopolitical, public-property right-of-way, transportation, and land use mapping. These data were used to model biomass production and pollution prevention potential, including harvest and transportation of biomass to the theoretical biorefinery location. From this, economic analysis and environmental protection analysis were conducted to test the approach’s ability to evaluate options with dual benefits.

2 Methods

2.1 Biorefinery Site Selection

A theoretical biorefinery location in Centralia, Washington, USA (46.7162° N, 122.9543° W) was used for mapping analysis. This location meets previously described economic guidelines for an ideal biorefinery sites (Bandaru, et al., 2015) due to low land costs and the location's need for an industry to improve a localized depressed economy (Chowyuk, et al., 2021; Hart, et al., 2018).

2.2 Roadside Poplar Supply and Cost

2.2.1 Vegetation Species Selection

Analysis was based on planting with hybrid poplar due to the large amount of data for poplar growth in the hypothetical study region (Chowyuk, et al., 2021; Chudy, et al., 2019). Hybrid poplar complies with three selection criteria for VFA vegetation: (1) non-invasive, perennial species adaptable to marginal land (Voinov, et al., 2015), (2) require minimal fertilizer/herbicide while providing high yield (Voinov, et al., 2015), (3) comply with local roadside vegetation restrictions (e.g. WSDOT, 2003). Short-rotation poplar is a high-yield, perennial energy crop (PEC) (Dillen, et al., 2013) recognized for its suitability to sustainable cultivation (Ruf and Emmerling, 2021), adaptability to marginal land (Feng, et al., 2017; Ghezehei, et al., 2021), and minimal fertilizer and herbicide needs (Labrecque and Teodorescu, 2005). Poplar has previously been considered for tertiary treatment during wastewater reclamation (Chowyuk, et al., 2021; Kargol, et al., 2022). The approach in the current study is readily extended to other perennial bioenergy feedstocks, such as switchgrass or miscanthus.

2.2.2 Identification of Available Land

VFS land availability was identified using state and regional maps to identify the roadside land within transportation corridor right-of-ways and other public land that were adjacent to roadways. The Geographic Information System (GIS) mapping method approach is depicted in Figure 1. The geographic region was constructed by selecting the counties in Western Washington on the *County Layer* using a Washington State County vector digital data map (WADNR, 2021). The northern edge was defined by the political boundary with Canada, the southern edge was defined by the political boundary with the state of Oregon, USA, the western boundary was defined by the Pacific Ocean, and the eastern boundary was defined by limitation of transportation corridors through the Cascade mountains. All the other map layers were clipped to conform to the shape of Western Washington. Public right-of-way land was identified as non-taxed land (i.e. blank spaces) on a tax parcel map (WAGeoservices, accessed 2019). The tax parcel map was inverted to omit taxed parcels, and overlayed with major transportation routes defined on a road map (WSDOT, 2019) and road surface areas (WSDOT, 2022b)was subtracted to construct a right-of-way map. A visual depiction for the construction of the right-of-way map is shown in Supplemental Information Figure 1. Finally, the land use of the right-of-way areas was mapped using a land cover map (MRLC, 2016; Wickham, et al., 2021). In the land cover map, lands are is classified as open land, water, developed land, barren land, forest, shrubland, grassland, cultivated land, and wetlands (MRLC, 2016). We selected open land, barren land, shrubland, and grassland as land potentially available for VFSs (Figure 1, Step 5). The result was a final map depicting the state right-of-way in Western Washington with areas that were available for VFS sites.

2.2.3 Biomass Yields, Production Cost, and Transportation

For the current study, production cost models included harvest and transportation costs while establishment, maintenance, and site re-establishment costs were assumed to be incurred by the transportation corridor authority responsible for the ecosystem services benefit of the VFSs. Modeled costs of biomass production were calculated as:

$$Plant\ Gate\ Cost = Transportation\ Cost + Harvest\ Cost \qquad \text{Eq. (1)}$$

where Plant Gate Cost refers to the cost of the feedstock at the entrance to the biorefinery on a per mass basis. Harvest costs were set at \$30.15 per Mg as determined previously (Chowyuk, et al., 2021) based on the GreenWood Resources Production Cost Calculator (Shuren, et al., 2018). Transportation costs were calculated as \$0.27 per Mg per km, including backhaul transportation costs following a previously described approach (Chowyuk, et al., 2021). Network Analyst on GIS was used to calculate the transportation distances for each VFS site.

Biomass production was estimated using the assumption that roadside land was "marginal" such that biomass yield was 17.5 dry Mg·hectare^{-1}·year^{-1} (Chowyuk, et al., 2021). If land conditions were better than "marginal," the actual realized production could be higher than estimated.

2.2.4 Supply Curve Development

The values for Eq 1 for each site were ranked from the lowest to highest. A supply curve was generated assuming that the biorefinery would use the least expensive biomass source first. As the biorefinery's capacity increased, the next cheapest source of biomass was integrated into the supply. A moving average of this function was applied to determine the average biomass cost for a specified biorefinery capacity.

2.3 Pollution Reduction

2.3.1 Roadway Surface Area and Habitat Sensitivity

The total surface area of the major roadways (A_R) was determined by buffering major route lines on a *Roadway Area Layer* (WSDOT, 2022a) with their roadway widths using the *Lanes Layer* (WSDOT, 2022b), as depicted in Supplemental Information Figure 2. Urban and rural roadways were classified (WSDOT, 2022c) to reflect the differing pollutant concentrations associated with the road runoff from each classification (WSDOT, 2015). The roadways were further classified as high, moderate, low, and no sensitivity based on data from WSDOT inventories (WSDOT, 2018) to create an *Aquatic Sensitivity Roadway Area Layer*.

2.3.2 Annual Storm Load

The annual storm load was modeled as the mass of a pollutant in runoff per year and was calculated as:

$$L = EMC * R * \left(A_R - A_{VFS} * E_f\right) \qquad Eq. (2)$$

where L is the annual storm pollutant load in mass per year, EMC is the rainfall event mean concentration in the roadway runoff, R is the annual average depth of rainfall, A_R is the roadway area, A_{VFS} is the roadway area that is served by a VFS, and E_f is efficiency of pollutant removal by the VFS. Table 1 shows the EMC and E_f values used in Eq 2. The ECM values were obtained from the Washington State Department of Transportation (WSDOT) Highway Runoff Characterization Report (WSDOT, 2015). Values from four publications (Cahill, et al., 2018; Clary, et al., 2017; Dillaha, et al., 1989; USDOT, 1997) were reviewed to determine the E_f for use in Eq 2. R was set at the average annual rainfall depth for Western Washington.

3 Results

3.1 Land Availability and Poplar Supply Curve

Error! Reference source not found. shows the result of the land availability analysis. This consisted of 5,600 hectares (56 km^2) of roadside land in Western Washington available for conversion to VFS sites. Of this, an estimated 26 km^2 are currently mowed under the WSDOT Regional Integrated Roadside Vegetation Management (IRVM) plans (Clark and Willard, 2022; Donk and Willard, 2022; Elley, et al., 2022; Golden, et al., 2022; Hastings and Willard, 2022; Joyce and Willard, 2022; Nowels and Willard, 2022; Rae, et al., 2022; Renshaw, et al., 2022; Schiller, et al., 2022; Sexton and Willard, 2022; Stryker, et al., 2022; VanAntwerp and Willard, 2022) . Our analysis showed that the area of land converted to VFS could be doubled over the IRVM plan estimates by adding open land, barren land, and shrubland, validating that the GIS land use analysis approach aligned with open roadside lands recognized by regional transportation authorities.

Figure 3 shows the model of poplar supply costs compared to the fraction of roadside poplar (with the balance of poplar being from dedicated tree farms). If all areas in Figure 2 were developed as VFS, the total poplar yield would be 97 dry Gg biomass per year. The cost of the VSF poplar (Eq 1) increased with distance from the biorefinery, visualized as the increased trend in the dotted line on Figure 3. Roadside poplar was 50% to 70% the cost of dedicated poplar. The combined supply curve shown in Figure 3 was constructed using the next cheapest biomass source as the supply increases. When the supply required by the biorefinery exceeded the maximum roadside supply (97 dry Gg per year), the averaged cost was similar to the cost of dedicated poplar ($73 and $74 per dry Mg for averaged and dedicated poplar, respectively). Close-proximity dedicated poplar was less expensive than the roadside poplar beginning at 54 dry Gg per year. For biorefinery demands above this annual biomass value, a combined poplar source was the most cost effective.

3.2 Predicted Pollution Reduction

Figure 4 shows the results of the urban-rural road surface area analysis (total area) compared to road surface areas associated with potential VFS sites from Figure 2. The urban road surface area was substantially higher than the rural surface area for the study region, while the rural surface areas were more amenable to VFS and proportionally more often associated with sensitive habitats. Roadways near highly sensitive aquatic areas are important to this analysis because these represent the largest environmental impact. As shown in Figure 4, 51% of the urban road surface area and 77% of the rural road surface area near highly sensitive aquatic areas could be retrofitted with VFSs.

Figure 5 shows the annual storm load calculated using Eq 2 applied to the road areas in Western Washington. The poplar VFS would remove approximately 26% of TSS, 13% of TP, 13% of TKN, 23% of total Cu, 14% of dissolved Cu, 26% of total Zn, 20% of dissolved Zn, 20% of total Pb, and 13% of dissolved Pb from roadway runoff.

Figure 6 shows the pollutant reduction through VFS implementation on urban highway roadsides in Western Washington broken down by aquatic sensitivity. Pollutant reduction is predicted for each aquatic sensitivity designation (high, medium, low, none). While there was greater road surface area in the urban areas (Figure 4), the higher portion of land amenable to VFS and the higher proximity to sensitive aquatic habitats suggests that VFS by rural roadways have higher potential for pollution reduction than their urban counterparts.

4 Discussion

A main barrier to economic lignocellulosic liquid biofuels is feedstock costs (Stanton and Gustafson, 2019). Cultivation of large-scale lignocellulose plantations is often not considered a viable option (Chudy, et al., 2019). Dual-purpose growth of lignocellulosic poplar for its ecosystem services can improve the economics of the feedstock (Chowyuk, et al., 2021; Hart, et al., 2018). The objective of this research was to examine the potential for growing biomass for the dual purposes of reducing pollution in roadway runoff and supplying feedstock for a biorefinery. The research was applied to a fixed geographic region to enable use of GIS approaches for a realistic analysis. The analysis showed that despite a broad range of transportation distances, the dual purpose VFS poplar could significantly off-set feedstock costs for a biorefinery. For a modest scale biorefinery, 150 Gg biomass per year, we calculate a $1.35 million annual reduction in biomass cost. A first biorefinery would be smaller than 150 Gg biomass per year to save on capital cost and having such a substantial savings in biomass cost might be necessary for financial viability. Even a large biorefinery would be constantly looking for lower cost biomass and would welcome feedstock used to clean stormwater. Taking advantage of feedstock grown to receive wastewater (Chowyuk, et al., 2021) would enable a biorefinery to build a substantial 300 Gg biomass per year and still have a biomass cost close to $64 per Mg, saving $4.5 million per year compared purchasing dedicated poplar feedstock. Another advantage, while not included in the ecosystem analysis, is that there would be benefits, including decreased land-use-change carbon emissions and potentially impacting land growing food crops, in reducing the land converted to dedicated poplar growth plantations.

The environmental benefits of have extensive VFSs on roadways are substantial. The environmental impact analysis shows a substantial reduction of pollutant loads in sensitive aquatic areas by planting VFSs. Half of all urban roadways and one-third of all rural roadways in highly sensitive aquatic areas can be treated with VFSs. The reduction in pollution loading by implementing the VFSs in these sensitive areas ranged from 10% to 40% depending on the pollutant. Notably, toxic metals such as copper, zinc, and lead were predicted to have the most effective removal.

Operational details that address regional realities would need to be evaluated before implementation of roadside biomass production system. For example, poplar may not be the best biomass species for all regions, but the results would be similar with other types of biomass. Importantly, the results shown here demonstrate that substantial economic and environmental benefits are achievable by growing biomass for both cleaning stormwater and for biorefinery feedstock. It should be noted that the detailed results presented in this paper apply to the region of study. The paper does, however, present a rigorous approach to examining the use of VFSs biomass for biorefinery feedstock and similar results would be obtained from analysis of any region that has a significant transportation infrastructure.

5 Conclusion

Growing biomass to simultaneously provide ecosystem services and for biorefinery feedstock is a compelling concept that can advance the bioeconomy. In this study, we have shown that one approach to providing ecosystem services, growing roadside biomass, can produce cost-effective poplar biomass and reduce roadway runoff pollution loads. The results, presented here with poplar trees in Western Washington, are also adaptable for other crops and in other regions. Operational details would have to be worked out to have a commercial enterprise, but the results presented here support that the concept holds great potential and should be further developed. Future research is needed to clarify the variables that may influence stormwater pollution removal when growing biomass feedstock, and on how these variables, in turn, may impact biomass production.

6 Acknowledgements

This work was supported by the USDA National Institute of Food and Agriculture's Agriculture and Food Research Initiative Competitive Grant [grant number 2011-68005-30407]. The authors express their gratitude to Chris Gustafson and others at the Washington Department of Transportation for the data and input to this research.

References References

Bandaru, V., Parker, N.C., Hart, Q., Jenner, M., Yeo, B.L., Crawford, J.T., Li, Y.Z., Tittmann, P.W., Rogers, L., Kaffka, S.R. and Jenkins, B.M., 2015. Economic sustainability modeling provides decision support for assessing hybrid poplar-based biofuel development in california. Calif. Agric. 69, 171-176. 10.3733/ca.v069n03p171.

Barbosa, A.E. and Fernandes, J.N., 2021. Review of tools for road runoff quality prediction and application to european roads. Water Sci. Technol. 84, 2228-2241. 10.2166/wst.2021.427.

Barrett, M.E., Kearfott, P. and Malina, J.F., 2006. Stormwater quality benefits of a porous friction course and its effect on pollutant removal by roadside shoulders. Water Environ. Res. 78, 2177-2185. 10.2175/106143005x82217.

Boger, A.R., Ahiablame, L., Mosase, E. and Beck, D., 2018. Effectiveness of roadside vegetated filter strips and swales at treating roadway runoff: A tutorial review. Environ. Sci.-Wat. Res. Technol. 4, 478-486. 10.1039/c7ew00230k.

Bouchard, N.R., Osmond, D.L., Winston, R.J. and Hunt, W.F., 2013. The capacity of roadside vegetated filter strips and swales to sequester carbon. Ecol. Eng. 54, 227-232. 10.1016/j.ecoleng.2013.01.018.

Brown, A.E., Ford, J.S., Bale, C.S.E., Camargo-Valero, M.A., Cheffins, N.J., Mason, P.E., Price-Allison, A.M., Ross, A.B. and Taylor, P.G., 2020. An assessment of road -verge grass as a feedstock for farm -fed anaerobic digestion plants. Biomass Bioenerg. 138, 11. 10.1016/j.biombioe.2020.105570.

Cahill, M., Godwin, D. and Tilt, J., 2018. Vegetated filter strips: Low-impact development fact sheet, EM 9208, Oregon State University Extension Service, Corvallis, Oregon, USA. https://catalog.extension.oregonstate.edu/em9208/html

Chowyuk, A.N., El-Husseini, H., Gustafson, R.R., Parker, N., Bura, R. and Gough, H.L., 2021. Economics of growing poplar for the dual purpose of biorefinery feedstock and wastewater treatment. Biomass Bioenerg. 153, 9. 10.1016/j.biombioe.2021.106213.

Chudy, R.P., Busby, G.M., Binkley, C.S. and Stanton, B.J., 2019. The economics of dedicated hybrid poplar biomass plantations in the western u.S. Biomass Bioenerg. 124, 114-124. 10.1016/j.biombioe.2019.03.010.

Clark, B. and Willard, R., 2022. Southwest region, area 1, integrated roadside vegetation management plan, Washington State Department of Transportation, Maintenance Operations Division, Olympia, Washington, USA. https://wsdot.wa.gov/sites/default/files/2022-06/SWR_Area1_IRVMPlan_2022.pdf

Clary, J., Jones, J., Leisenring, M., Hobson, P. and Strecker, E., 2017. International stormwater bmp database 2016 summary statistics, Water Environment and Reuse Foundation, Alexandria, Virginia, USA. 2016_BMPDBSummaryStatistics_03-SW-1COh.pdf

Dillaha, T.A., Reneau, R.B., Mostaghimi, S. and Lee, D., 1989. Vegetative filter strips for agricultural nonpoint source pollution control. 32, 513-519. <Go to ISI>://WOS:A1989U356400025

Dillen, S.Y., Djomo, S.N., Al Afas, N., Vanbeveren, S. and Ceulemans, R., 2013. Biomass yield and energy balance of a short-rotation poplar coppice with multiple clones on degraded land during 16 years. Biomass Bioenerg. 56, 157-165. 10.1016/j.biombioe.2013.04.019.

Donk, T. and Willard, R., 2022. Northwest region, area 1, integrated roadside vegetation management plan, Washington State Department of Transportation, Maintenance Operations Division, Olympia, Washington, USA. https://wsdot.wa.gov/sites/default/files/2022-06/NWR_Area1_IRVMPlan_2022.pdf

Elley, G., Kendall, B. and Willard, R., 2022. Northwest region, area 5, integrated roadside vegetation management plan, Washington State Department of Transportation, Maintenance Operations Division, Olympia, Washington, USA. https://wsdot.wa.gov/sites/default/files/2022-06/NWR_Area5_IRVMPlan_2022.pdf

Feng, Q.Y., Chaubey, I., Engel, B., Cibin, R., Sudheer, K.P. and Volenec, J., 2017. Marginal land suitability for switchgrass, miscanthus and hybrid poplar in the upper mississippi river basin (umrb). Environ. Modell. Softw. 93, 356-365. 10.1016/j.envsoft.2017.03.027.

Flanagan, K., Branchu, P., Boudahmane, L., Caupos, E., Demare, D., Deshayes, S., Dubois, P., Meffray, L., Partibane, C., Saad, M. and Gromaire, M.C., 2018. Field performance of two biofiltration systems treating micropollutants from road runoff. Water Res. 145, 562-578. 10.1016/j.watres.2018.08.064.

Ghezehei, S.B., Ewald, A.L., Hazel, D.W., Zalesny, R.S. and Nichols, E.G., 2021. Productivity and profitability of poplars on fertile and marginal sandy soils under different density and fertilization treatments. Forests. 12, 17. 10.3390/f12070869.

Golden, M., Durst, G. and Willard, R., 2022. Northwest region, area 4, integrated roadside vegetation management plan, Washington State Department of Transportation, Maintenance Operations Division, Olympia, Washington, USA. https://wsdot.wa.gov/sites/default/files/2022-06/NWR_Area4_IRVMPlan_2022.pdf

Hart, N.M., Townsend, P.A., Chowyuk, A. and Gustafson, R., 2018. Stakeholder assessment of the feasibility of poplar as a biomass feedstock and ecosystem services provider in southwestern washington, USA. 9, 10.3390/f9100655.

Hastings, J. and Willard, R., 2022. Olympic region, area 1, integrated roadside vegetation management plan, Washington State Department of Transportation, Maintenance Operations Division, Olympia, Washington, USA. https://wsdot.wa.gov/sites/default/files/2022-06/OR_Area1_IRVMPlan_2022.pdf

Joyce, B. and Willard, R., 2022. Northwest region, area 2, integrated roadside vegetation management plan, Washington State Department of Transportation, Maintenance Operations Division, Olympia, Washington, USA. https://wsdot.wa.gov/sites/default/files/2022-06/NWR_Area2_IRVMPlan_2022.pdf

Kargol, A.K., Cao, C., James, C.A. and Gough, H.L., 2022. Wastewater reuse for tree irrigation: Influence on rhizosphere microbial communities. 9, 100063. https://doi.org/10.1016/j.resenv.2022.100063.

Karimi, H.A. and Liu, S., 2004. Developing an automated procedure for extraction of road data from high-resolution satellite images for geospatial information systems. J. Transp. Eng. 130, 621-631. 10.1061/(asce)0733-947x(2004)130:5(621).

Kayhanian, M., Suverkropp, C., Ruby, A. and Tsay, K., 2007. Characterization and prediction of highway runoff constituent event mean concentration. J. Environ. Manage. 85, 279-295. 10.1016/j.jenvman.2006.09.024.

Labrecque, M. and Teodorescu, T.I., 2005. Field performance and biomass production of 12 willow and poplar clones in short-rotation coppice in southern quebec (canada). Biomass Bioenerg. 29, 1-9. 10.1016/j.biombioe.2004.12.004.

Li, M.H., Barrett, M.E., Rammohan, P., Olivera, F. and Landphair, H.C., 2008. Documenting stormwater quality on texas highways and adjacent vegetated roadsides. J. Environ. Eng.-ASCE. 134, 48-59. 10.1061/(asce)0733-9372(2008)134:1(48).

[map] MRLC, 2016. Nlcd 2016 land cover (conus). United States Geological Survey (USGS), Multi-Resolution Land Characteristics (MRLC) Consortium, Sioux Falls, South Dakota, USA. https://www.mrlc.gov/data

Nowels, C. and Willard, R., 2022. Southwest region, area 2, integrated roadside vegetation management plan, Washington State Department of Transportation, Maintenance Operations Division, Olympia, Washington, USA. https://wsdot.wa.gov/sites/default/files/2022-06/SWR_Area2_IRVMPlan_2022.pdf

Pennington, D., Gould, M.C., Seamon, M., Knudson, W., Gross, P. and McLean, T., 2012. Expanding bioenergy crops to non-traditional lands in michigan, University of Michigan-Extension and Pure Michigan Energy Office, https://www.canr.msu.edu/uploads/files/F2F/DELEG%20draft%20report%2004-03-2012%20Final.pdf

Rae, C., Bergeman, N. and Willard, R., 2022. Olympic region, area 3, integrated roadside vegetation management plan, Washington State Department of Transportation, Maintenance Operations Division, Olympia, Washington, USA. https://wsdot.wa.gov/sites/default/files/2022-06/OR_Area3_IRVMPlan_2022.pdf

Renshaw, M., Edwards, B. and Willard, R., 2022. Northwest region, area 3, integrated roadside vegetation management plan, Washington State Department of Transportation, Maintenance Operations Division, Olympia, Washington, USA. https://wsdot.wa.gov/sites/default/files/2022-06/NWR_Area3_IRVMPlan_2022.pdf

Ruf, T. and Emmerling, C., 2021. Different life-form strategies of perennial energy crops and related nutrient exports require a differentiating view specifically concerning a sustainable cultivation on marginal land. GCB Bioenergy. 13, 893-904. 10.1111/gcbb.12830.

Schiller, B., Whitehill, C. and Willard, R., 2022. Olympic region, area 4, integrated roadside vegetation management plan, Washington State Department of Transportation, Maintenance Operations Division, Olympia, Washington, USA. https://wsdot.wa.gov/sites/default/files/2022-06/OR_Area4_IRVMPlan_2022.pdf

Sexton, C. and Willard, R., 2022. Southwest region, area 3, integrated roadside vegetation management plan, Washington State Department of Transportation, Maintenance Operations Division, Olympia, Washington, USA. https://wsdot.wa.gov/sites/default/files/2022-06/SWR_Area3_IRVMPlan_2022.pdf

Shokri, M., Kibler, K.M., Hagglund, C., Corrado, A., Wang, D.B., Beazley, M. and Wanielista, M., 2021. Hydraulic and nutrient removal performance of vegetated filter strips with engineered infiltration media for treatment of roadway runoff. J. Environ. Manage. 300, 11. 10.1016/j.jenvman.2021.113747.

Shuren, R.A., Busby, G. and Stanton, B.J., 2018. A biomass product cost calculator: A decision tool for famers and investors, GreenWood Resources, http://greenwoodresources.com/wp-content/uploads/2018/04/A-Biomass-Production-Cost-Calculator-PDF.pdf

Stanton, B.J. and Gustafson, R.R., 2019. Advanced hardwood biofuels northwest: Commercialization challenges for the renewable aviation fuel industry. Appl. Sci.-Basel. 9, 14. 10.3390/app9214644.

Stryker, D., Smiley, J. and Willard, R., 2022. Olympic region, area 2, integrated roadside vegetation management plan, Washington State Department of Transportation, Maintenance Operations Division, Olympia, Washington, USA. https://wsdot.wa.gov/sites/default/files/2022-06/OR_Area2_IRVMPlan_2022.pdf

USDOT, 1997. Fact sheet - filter strips, Stormwater Best Management Practices in an Ultra-Urban Setting: Selection and Monitoring. United States Department of Transportation, Federal Highway Administration, Washington, D.C., USA. https://www.environment.fhwa.dot.gov/env_topics/water/ultraurban_bmp_rpt/3fs11.aspx

Van Meerbeek, K., Muys, B. and Hermy, M., 2019. Lignocellulosic biomass for bioenergy beyond intensive cropland and forests. Renew. Sust. Energ. Rev. 102, 139-149. 10.1016/j.rser.2018.12.009.

VanAntwerp, B. and Willard, R., 2022. Southwest region, area 4, integrated roadside vegetation management plan, Washington State Department of Transportation, Maintenance Operations Division, Olympia, Washington, USA. https://wsdot.wa.gov/sites/default/files/2022-06/SWR_Area4_IRVMPlan_2022.pdf

Voinov, A., Arodudu, O., van Duren, I., Morales, J. and Qin, L., 2015. Estimating the potential of roadside vegetation for bioenergy production. J. Clean Prod. 102, 213-225. 10.1016/j.jclepro.2015.04.034.

[map] WADNR, 2021. Washington county boundaries [gis dataset]. Washington Department of Natural Resources, Olympia, Washington, USA. https://data-wadnr.opendata.arcgis.com/documents/wa-county-boundaries-download/about

[map] WAGeoservices, accessed 2019. Current parcels: Washington statewide tax parcel data for gis users. Washington Geospatial Open Data Portal, Olympia, Washington, USA. https://geo.wa.gov/datasets/wa-geoservices::current-parcels/about

Wickham, J., Stehman, S.V., Sorenson, D.G., Gass, L. and Dewitz, J.A., 2021. Thematic accuracy assessment of the nlcd 2016 land cover for the conterminous united states. 257, 112357. https://doi.org/10.1016/j.rse.2021.112357.

Winston, R.J., Anderson, A.R. and Hunt, W.F., 2017. Modeling sediment reduction in grass swales and vegetated filter strips using particle settling theory. J. Environ. Eng.-ASCE. 143, 11. 10.1061/(asce)ee.1943-7870.0001162.

Winston, R.J. and Hunt, W.F., 2017. Characterizing runoff from roads: Particle size distributions, nutrients, and gross solids. J. Environ. Eng.-ASCE. 143, 12. 10.1061/(asce)ee.1943-7870.0001148.

WSDOT, 2003. Roadside manual, M 25-30.05, Washington State Department of Transportation, Development Division, Design Office, Engineering and Regional Operations, https://www.wsdot.wa.gov/publications/manuals/fulltext/M25-30/Roadside.pdf

WSDOT, 2015. Npdes municipal stormwater permit final highway runoff characterization report (s7 . B) water years 2012-2014, Washington State Department of Trasnportation, Olympia, Washington, USA.

[map] WSDOT, 2018. Sensitive aquatic areas [gis dataset]. WSDOT Online Map Center. Washington State Department of Transportation, Olympia, Washington, USA. https://gisdata-wsdot.opendata.arcgis.com/datasets/WSDOT::wsdot-sensitive-aquatic-areas/about

[map] WSDOT, 2019. Historic state route data (1:24k) [gis dataset]. WSDOT Online Map Center. Washington State Department of Transportation, Olympia, Washington, USA. https://gisdata-wsdot.opendata.arcgis.com/maps/wsdot-historic-state-route-data-124k-2019/about

[map] WSDOT, 2022a. Roadway data lane information [gis dataset]. WSDOT Online Map Center. Washington State Department of Transportation, Olympia, Washington, USA. https://gisdata-wsdot.opendata.arcgis.com/datasets/WSDOT::wsdot-roadway-data-lane-information-1/about

[map] WSDOT, 2022b. Roadway data roadway width [gis dataset]. WSDOT Online Map Center. Washington State Department of Transportation, Olympia, Washington, USA. https://gisdata-wsdot.opendata.arcgis.com/datasets/WSDOT::wsdot-roadway-data-roadway-width/about

[map] WSDOT, 2022c. Roadway data urban rural [gis dataset]. WSDOT Online Map Center. Washington State Department of Transportation, Olympia, Washington, USA. https://gisdata-wsdot.opendata.arcgis.com/datasets/WSDOT::wsdot-roadway-data-urban-rural-1/about

Wu, J.S. and Allan, C., 2018. Vegetated swales for managing stormwater runoff from secondary roads. J. Environ. Eng.-ASCE. 144, 10. 10.1061/(asce)ee.1943-7870.0001447.

Table 1. Values used in Eq 2 for Average Event Mean Concentration (EMC) and vegetated filter strip (VFS) removal efficiencies (E_f).

	TSS	**TP**	**TKN**	**Cu, Total**	**Cu, Dissolved**	**Zn, Total**	**Zn, Dissolved**	**Pb, Total**	**Pb, Dissolved**
	Average Event Mean Concentration (EMC)								
Roadway Class	mg/L	mg/L	mg/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Urban	61.25	0.12	1.57	33.21	12.94	126.22	14.31	5.86	0.18
Rural	61.50	0.08	1.46	16.38	4.87	66.61	4.72	4.67	0.12
Reference	**Vegetated Filter Strip Removal Efficacy (E_f)**								
Clary, 2017	50%	-14%	20%	52%	36%	68%	47%	41%	32%
Cahill, 2018	35-60%	60-65%	30-45%	*nr*	*nr*	*nr*	*nr*	*nr*	*nr*
USDOT, 1997	70%	10%	30%	40-50%	*nr*	40-50%	*nr*	40-50%	*nr*
Dillaha, 1989	50%	20%	20%	40%	40%	40%	40%	40%	40%
Study values	**50%**	**20%**	**20%**	**50%**	**36%**	**50%**	**40%**	**40%**	**30%**

Notes: TSS, total suspended solids; TP, total phosphorus; TKN, total kjeldahl nitrogen; nr, not reported. EMC values were obtained from (WSDOT, 2015). E_f *values were from (Cahill, et al., 2018; Clary, et al., 2017; Dillaha, et al., 1989; USDOT, 1997).*

7 Figure Captions

Figure1. Process for quantifying roadside land area availability using GIS mapping. Numbers in circles indicate the steps. (1) Overlay Land Cover Layer (A) with Buffered Major Routes Layer (B). (2) Clip Land Cover Layer with Buffered Major Routes Layer to produce Clipped Land Cover Layer (D) (3) Overlay Clipped Land Cover Layer (D) with Right-of-Way Layer (E). (4) Clip Clipped Land Cover Layer with Right-of-Way Layer to produce Right-of-Way Land Cover Layer (G). (5) SELECT open land, barren land, shrubland, and grassland from Right-of-Way Land Cover Layer to produce VFS Layer (H).

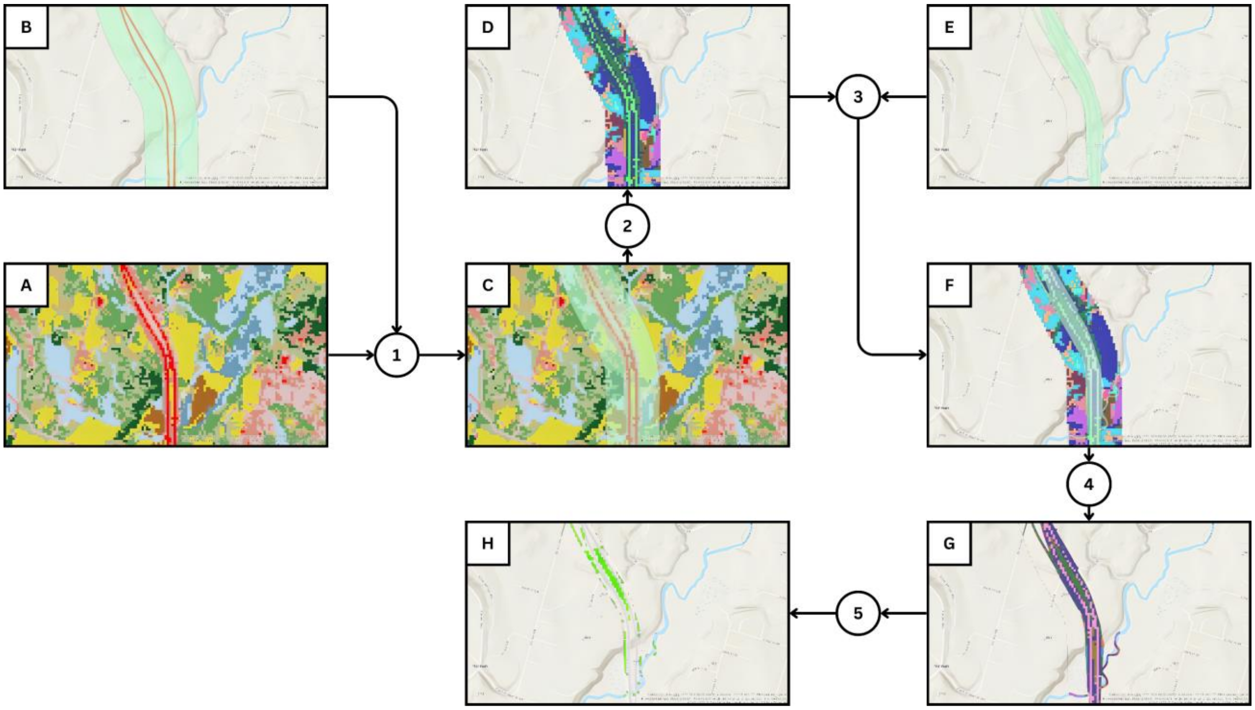
Figure 2. GIS mapping analysis showing land availability for vegetated filter strips in Western Washington, USA. The map was generated following the approach visualized in Figure 1. The yellow square shows the modeled location of the biorefinery. The pink circles represent potential VFS sites; size of the circle is relative to the available land at each site. The dashed pink line shows the political boundary between the USA and Canada.

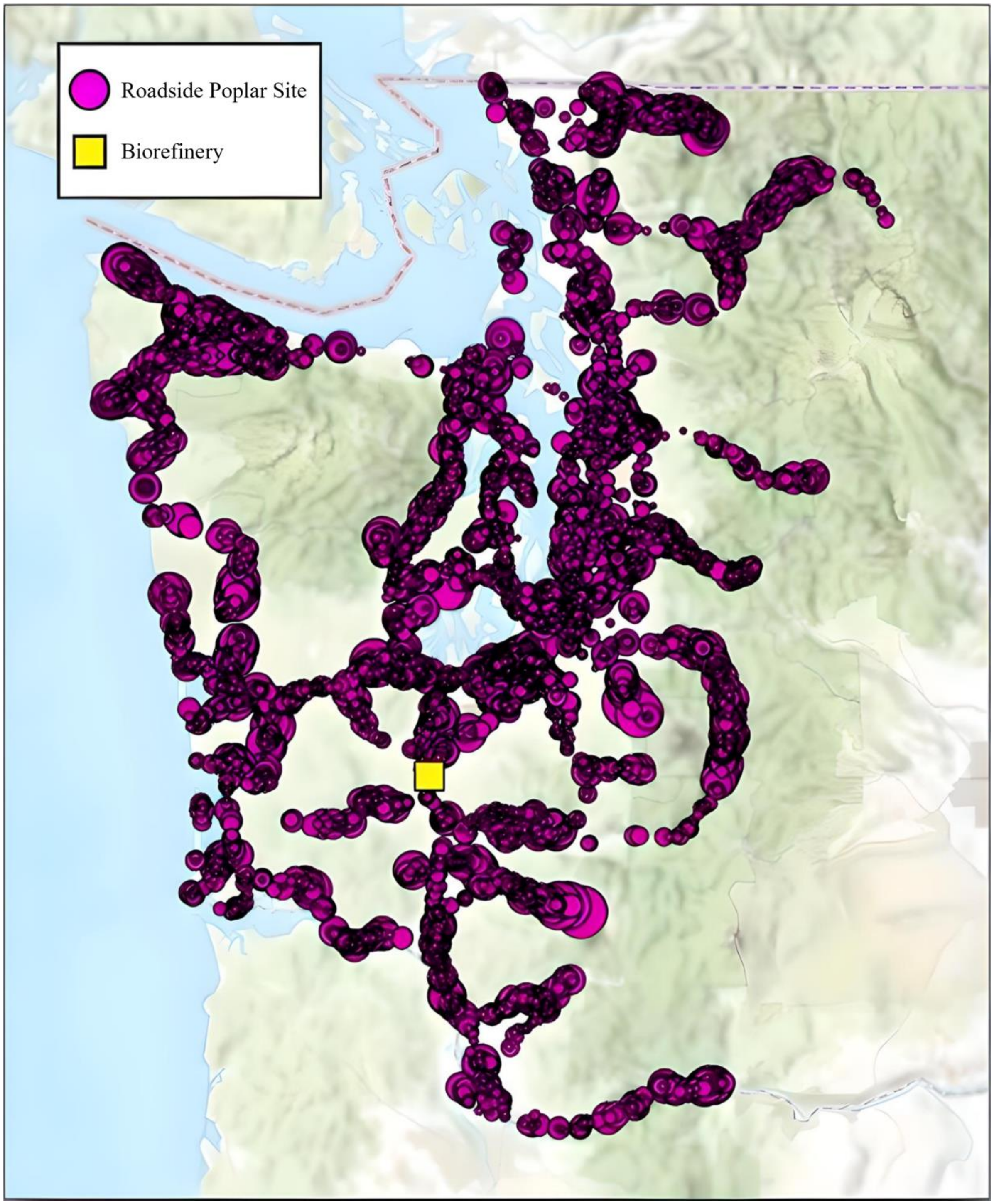
Figure 3. Supply Curve for a biorefinery using a combination of dedicated and roadside poplar. The “+” symbol marks the spot on the combined supply curve above which use of both dedicated and roadside poplar became most cost effective.

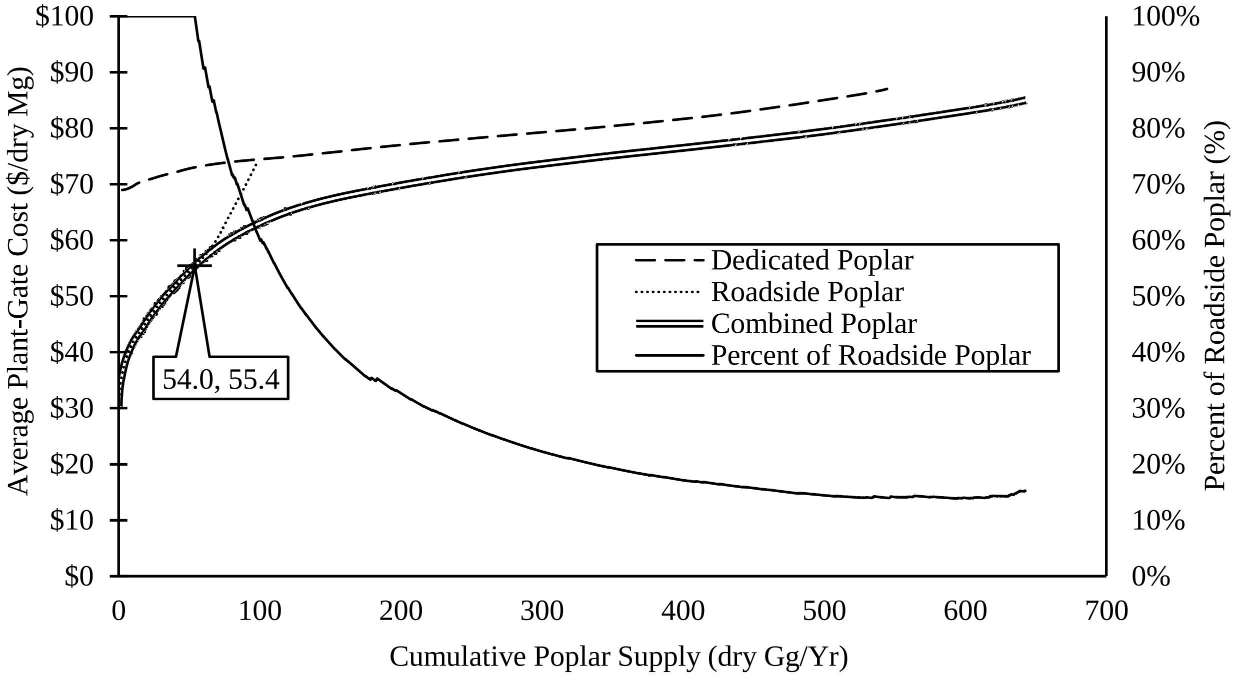
Figure 4. Roadway surface area characterized by surroundings (urban/rural) and near-by aquatic sensitivity (high/medium/low/none). Shading shows the portion of the total roadway surface area with potential for roadside vegetated filter strips (VFS). Habitat sensitivity was defined by the “Sensitive Aquatic Areas” datasets provided by the Washington State Department of Transportation(WSDOT, 2018)

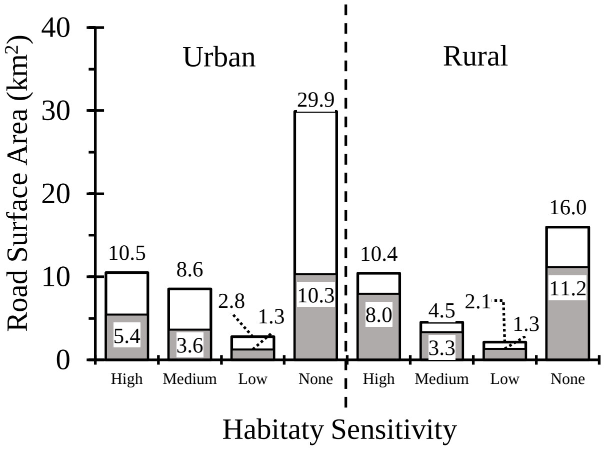
Figure 5. Modeled annual storm load calculated for Western Washington, USA. Hashed area shows the portion of the storm load predicted to be removed by installation of vegetated filter strips (VFS). TSS, total suspended solids; TP, total phosphorus; TKN, total kjeldahl nitrogen.

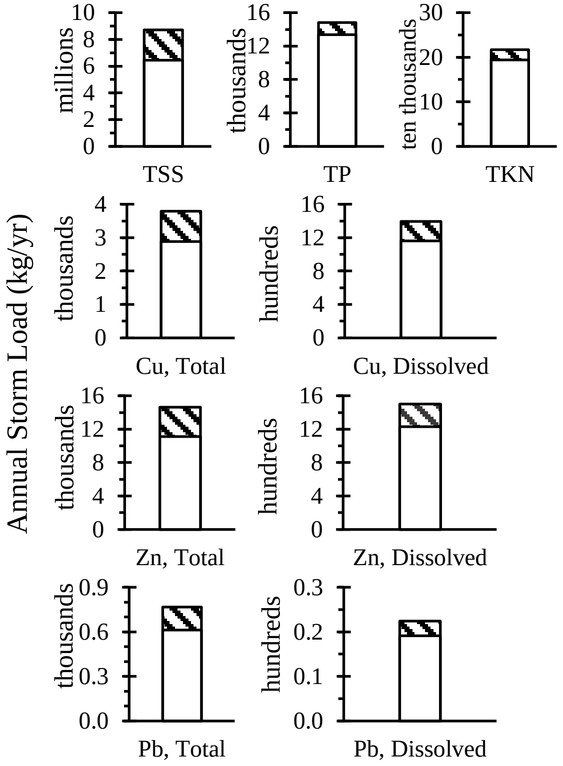
Figure 6. Modeled pollution reduction to aquatic habitats in (A) Urban Areas and (B) Rural Area of Western Washington based on the sensitivity of the habitat. TSS, total suspended solids; TP, total phosphorus; TKN, total kjeldahl nitrogen. Habitat sensitivity was defined by the "Sensitive Aquatic Areas" datasets provided by the Washington State Department of Transportation (WSDOT, 2018).


B
D
E
3
2
A
1
C
F
4
H
5
G

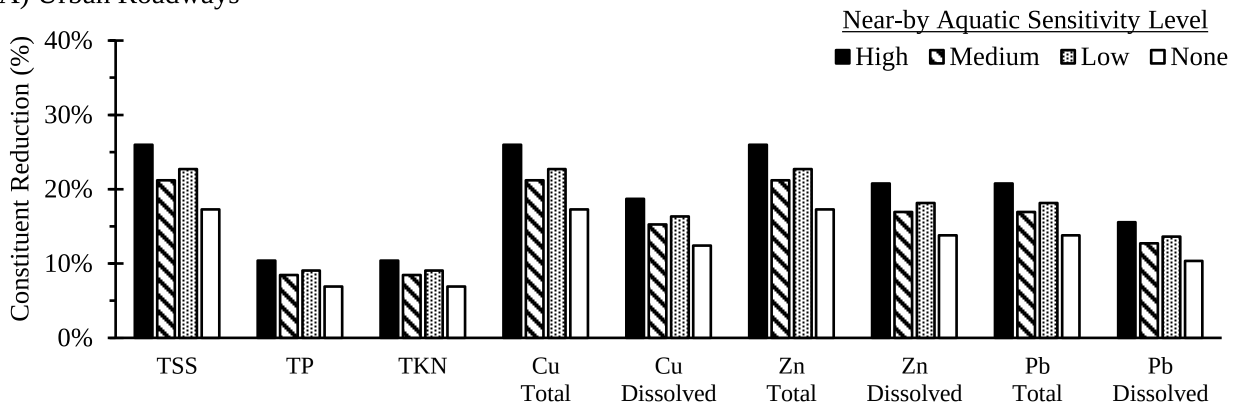

Roadside Poplar Site
Biorefinery


$100
$90
$80
$70
$60
$50
$40
$30
$20
$10
$0
Average Plant-Gate Cost ($/dry Mg)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percent of Roadside Poplar (%)
0
100
200
300
400
500
600
700
Cumulative Poplar Supply (dry Gg/Yr)
54.0, 55.4
Dedicated Poplar
Roadside Poplar
Combined Poplar
Percent of Roadside Poplar


Urban
Rural
Road Surface Area (km^2)
0
10
20
30
40
10.5
5.4
8.6
3.6
2.8
1.3
29.9
10.3
10.4
8.0
4.5
3.3
2.1
1.3
16.0
11.2
High
Medium
Low
None
High
Medium
Low
None
Habitaty Sensitivity


Annual Storm Load (kg/yr)
millions
10
8
6
4
2
0
TSS
thousands
16
12
8
4
0
TP
ten thousands
30
20
10
0
TKN
thousands
4
3
2
1
0
Cu, Total
hundreds
16
12
8
4
0
Cu, Dissolved
thousands
16
12
8
4
0
Zn, Total
hundreds
16
12
8
4
0
Zn, Dissolved
thousands
0.9
0.6
0.3
0.0
Pb, Total
hundreds
0.3
0.2
0.1
0.0
Pb, Dissolved

A) Urban Roadways



B) Rural Roadways