Modeling the effects of connected impervious surfaces on urban green spaces and groundwater recharge in a semi-arid environment

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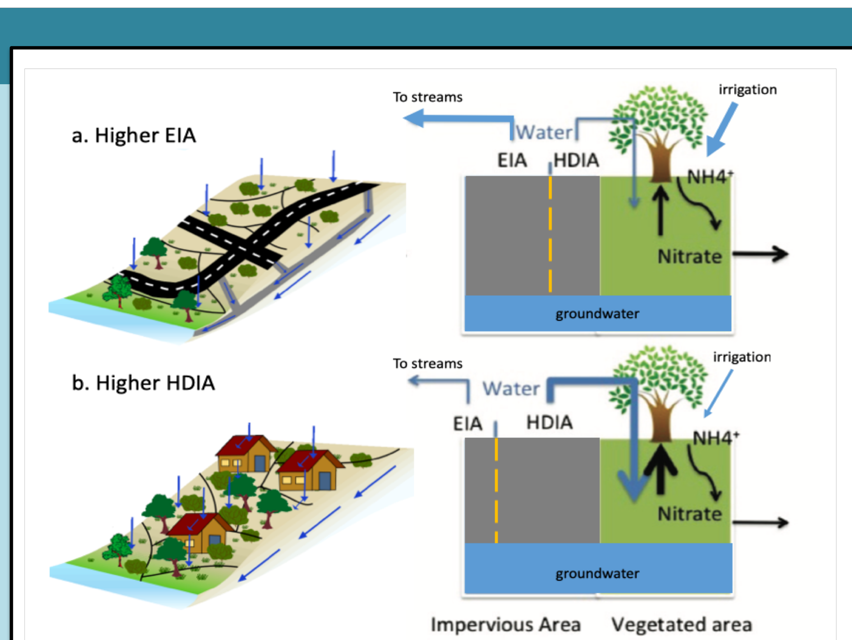
Abstract

Rapid urban population expansion in the U.S. Southwest and all over the world has led to paving over the natural landscape with impervious surfaces, altering the hydrology and biogeochemical cycling within a city. Conventional stormwater infrastructure routes most surface flows directly to streams, decreasing the opportunities for groundwater recharge and elevating pollutants in the stream. This has led to increased storm flows and potentially harmful nitrogen loading in coastal waters but has shown to be offset by green infrastructure or vegetated patches within cities. For vegetated patches to act as a more effective stormwater management technique, impervious surfaces disconnected from downstream waters or sewers can route surface flows instead to the vegetated patches. Previous studies show that the amount of impervious area that is connected to the drainage network (effective impervious area, EIA) may have a greater effect on the hydrology than the total amount of impervious area (TIA). We examine the effect that varying levels of both TIA and EIA will have on streamflow, groundwater recharge rates, and nitrate levels in both the stream and soils for three vegetated scenarios. We use a distributed ecohydrologic model, the Regional Hydro-Ecological Simulation System (RHESSys), to estimate the hydrologic and nitrate fluxes within a hillslope in Santa Barbara, a semi-arid coastal city. In areas like Santa Barbara where water is limited, providing vegetated patches with runoff from nearby impervious surfaces may also act as indirect irrigation. This work could potentially inform alternative irrigation strategies for urban water management.

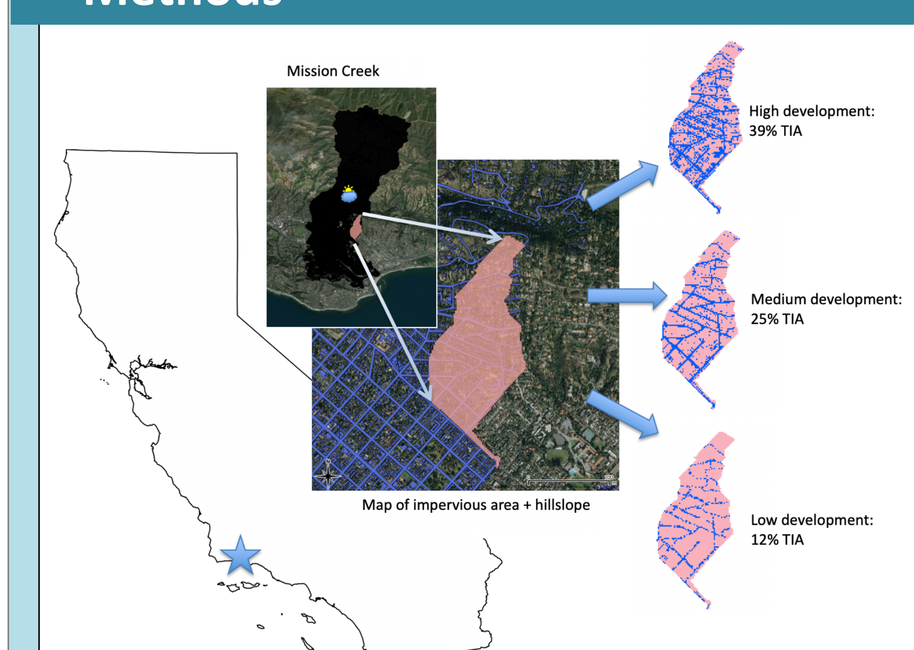
Motivation

In Santa Barbara, during storms steep slopes combined with conventional stormwater infrastructure route most surface flows directly to streams and into the ocean, decreasing the amount of water and nutrients for plants to uptake and elevating potentially harmful nitrogen loading to the nearshore coastal ecosystem. Connecting impervious surfaces to interstitial green spaces within the urban environment may be a way to reduce these effects.



Different scenarios of (a) high effective impervious area (EIA), which routes more surface flows to streams, resulting in less groundwater recharge and less nutrient availability in green spaces, and (b) high hydrologically disconnected impervious area, which routes surface flows to green space instead of stormwater drains, increasing groundwater recharge and plant nitrate availability.

Methods



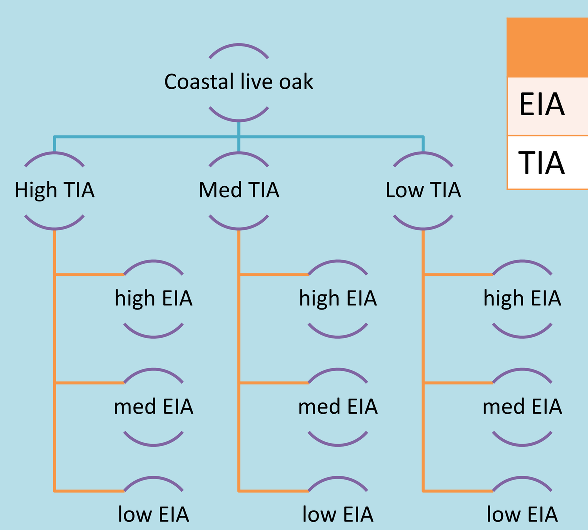
Location: Hillslope in Santa Barbara, CA
Average Temperature: 17.4°C
Average annual rainfall: 400mm
Hillslope area: 0.56km^2 (39% developed)

Model simulations were run for a 10-year time period with varying total impervious area (TIA), effective impervious area (EIA), and vegetation. Inputs include climate data and land cover data. Different EIA/TIA maps were derived from an impervious surface area map from Beighley et al. 2009.

Model Set–Up

Vegetation Types:
1) Coastal live oak
2) Chaparral – representative of xeric landscaping
3) Turfgrass
4) Turfgrass with irrigation

For each vegetation scenario there were 3 TIA scenarios, then 3 EIA scenarios, for a total of 36 simulations. Climate inputs were not changed for each scenario, and land cover was held constant.

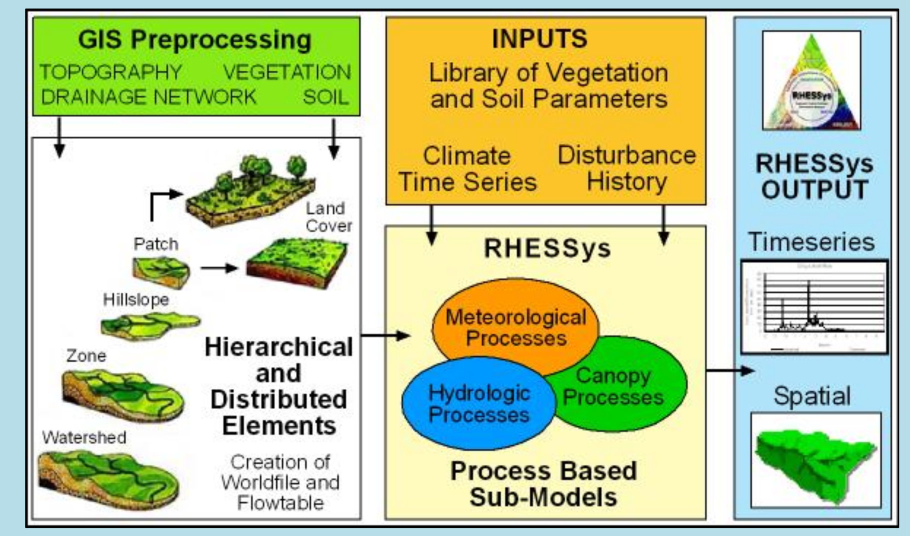


Each land cover scenario for vegetation, with coastal live oak as an example. The different levels of EIA were created based on the TIA level first.

	Low	Med	High
EIA	10%	50%	100%
TIA	12%	25%	39%

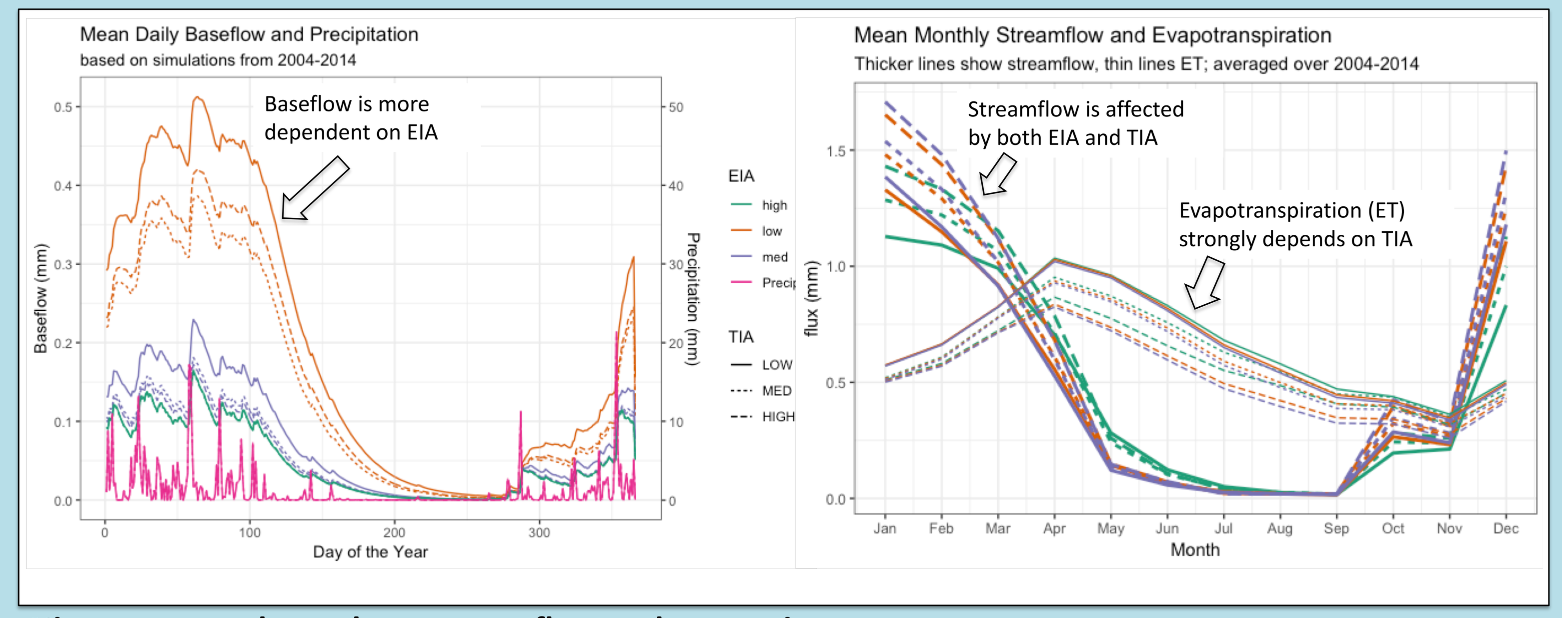
Model: Regional Hydro-Ecological Simulation System (RHESSys)

RHESSys simulates coupled carbon, water and nutrient cycling over spatially heterogeneous terrain. Daily temperature and precipitation inputs (for each spatial patch unit) influence:
a) Nitrate cycling
b) Vegetation nutrient uptake
c) Vegetation growth or senescence
d) Soil microbial processes
e) Respiration and Photosynthesis



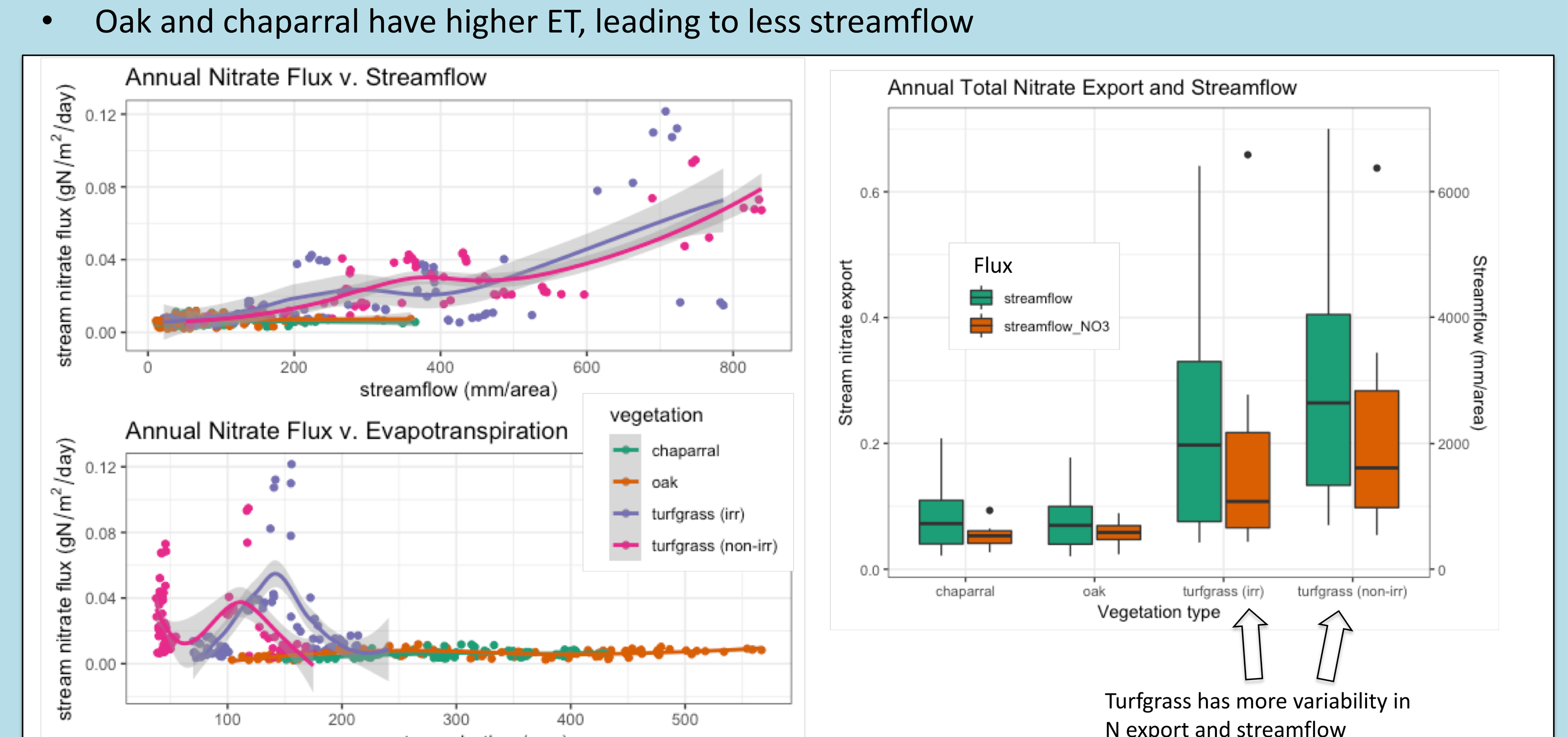
Results

Hydrologic fluxes for total impervious area (TIA) and connectivity (EIA) scenarios; averaged over all vegetation scenarios



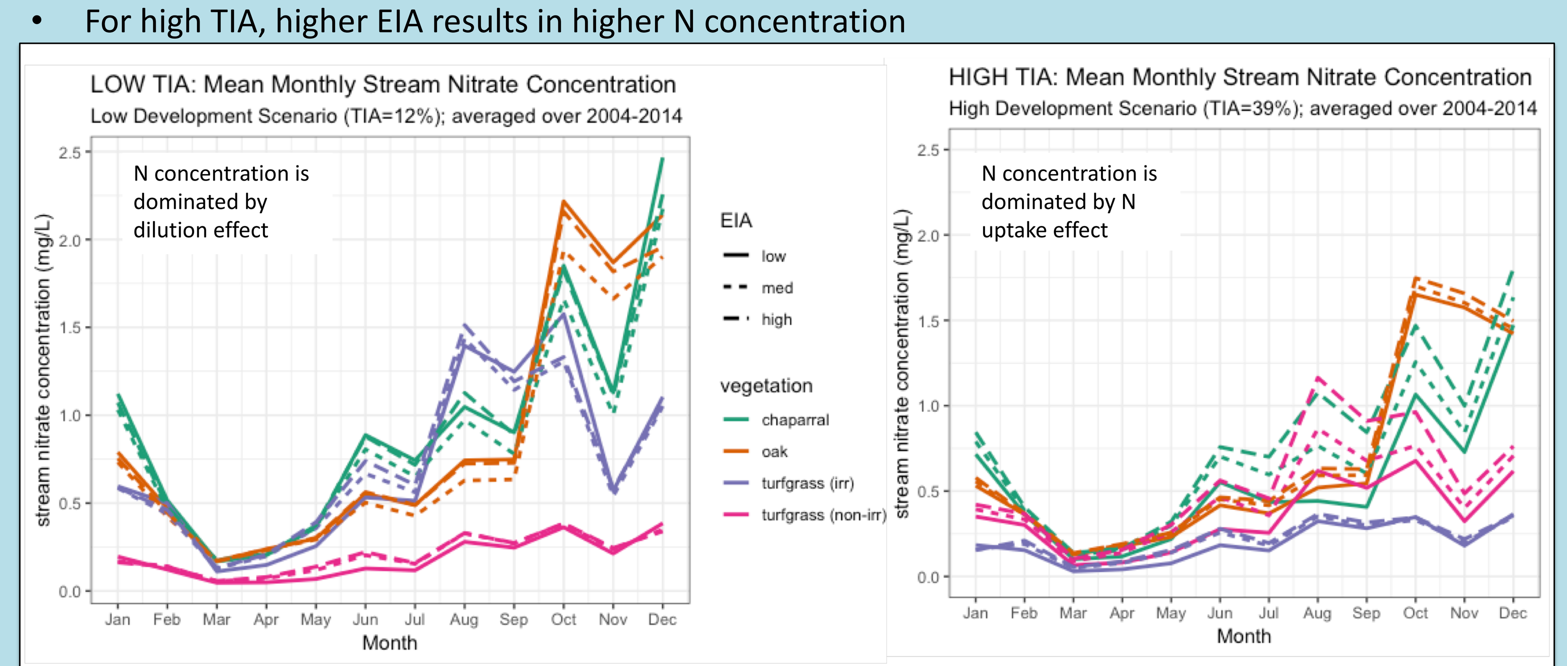
Nitrate export depends on streamflow and vegetation type

- Oak and Chaparral have higher nutrient uptake, leading to less nitrate exported to stream
- Oak and chaparral have higher ET, leading to less streamflow



Stream nitrate concentration varies with connectivity (EIA) and TIA

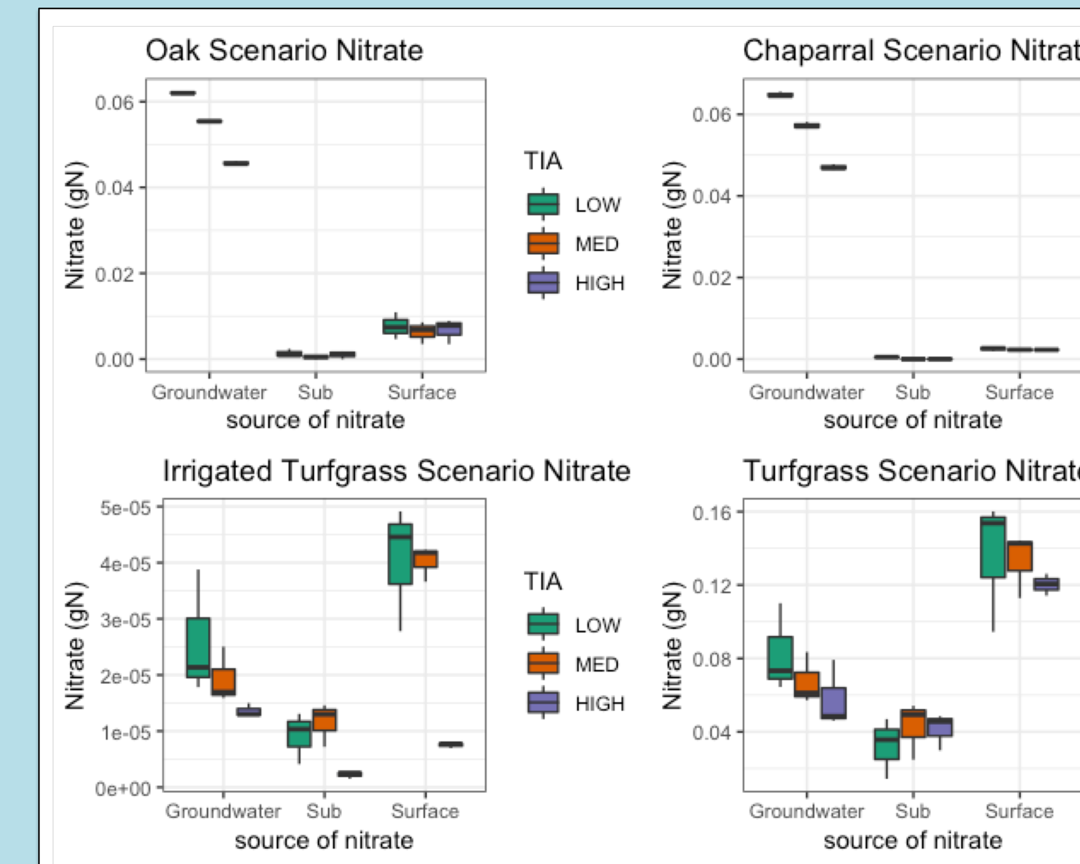
- Although N export is lower, N concentration is higher for oak and chaparral
- N concentrations are higher in the wetter months and for low TIA
- For low TIA, higher EIA results in lower N concentration
- For high TIA, higher EIA results in higher N concentration



Discussion

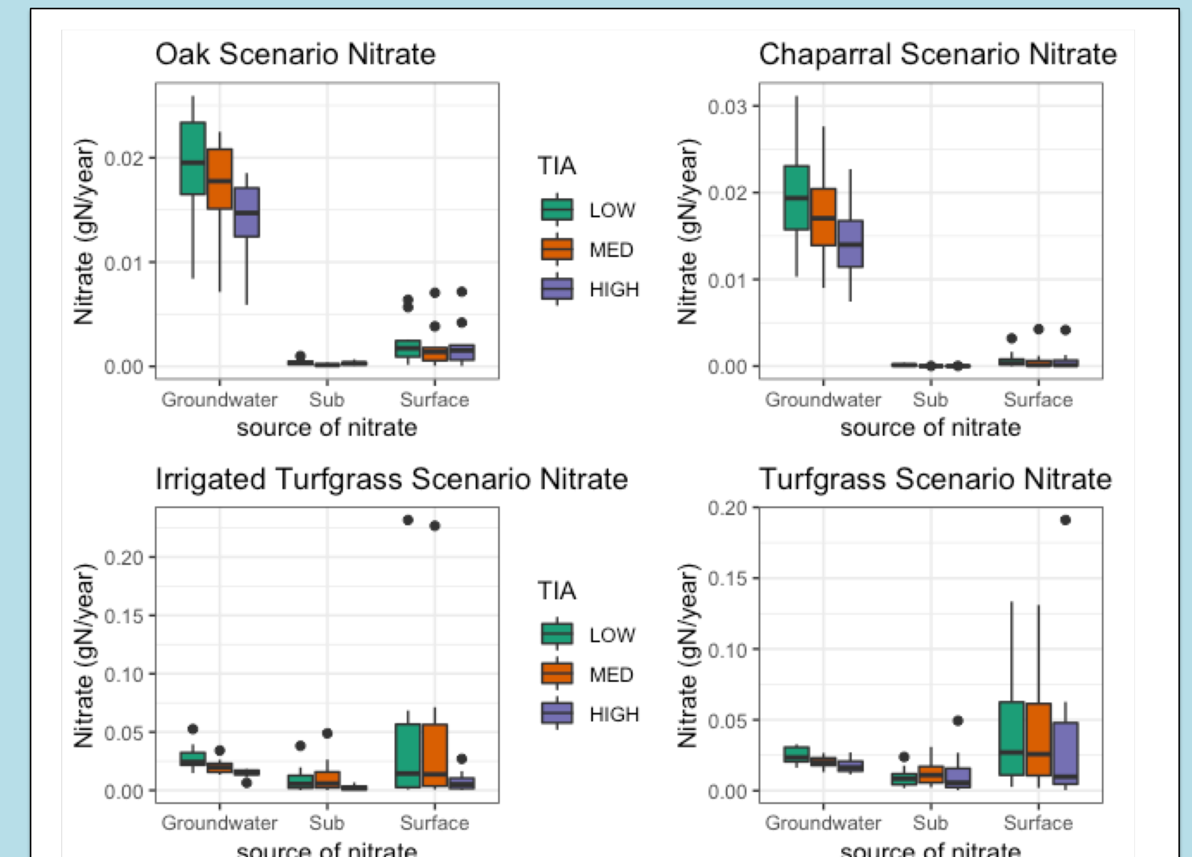
Variation in N export sources with EIA, by TIA and vegetation

- For oak and Chaparral, the vegetation with longer roots, N export occurs primarily from deeper groundwater, but this doesn't vary by EIA
- For both turfgrass scenarios, low EIA leads to more variation in N export from all sources
- For turfgrass scenarios N export occurs from all sources, but is greatest from the surface runoff.



Model output is the sum over the entire simulation period (2004-2014); boxplot width showing the variation due to EIA. The three sources of nitrate flux in the stream separated out by the model are: groundwater, surface, and subsurface.

Variation in N export sources with climate, by TIA and vegetation



Model output is the sum over all EIA scenarios; boxplot width showing the interannual variation. The model separates the source of stream nitrate flux into three different sources: groundwater, surface, and subsurface.

- For oak and Chaparral N export from groundwater varies more from climate than EIA
- For turfgrass scenarios, climate strongly influences surface export, with less effect on groundwater and shallow subsurface

Conclusion

- **Vegetation type effects streamflow and N export**
  - Oak and chaparral take up more N and water than turfgrass, but the increased water uptake dominates, leading to higher N concentrations
- **EIA effects on streamflow and N export change with TIA and vegetation**
  - Decreasing EIA is most effective at reducing N concentration when TIA is high and vegetation is deeply rooted (oak, chaparral)
  - When TIA is low, the effects of EIA is more complex and reducing EIA can sometimes lead to increasing N concentration by reducing dilution
- **Pathways of N export differ by vegetation type**
  - For deeply rooted plants, N export is dominated by deep groundwater sources
  - For turfgrass, groundwater, subsurface, and surface pathways are all important
- **Effects of interannual climate variation and EIA differ by N export pathway**
  - The effects of EIA is most notable for surface sources associated with turfgrass
  - Climate variability mostly impacts groundwater sources for deep rooted plants, and surface sources for turfgrass

Acknowledgements
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