Modeling the Structure and Functions of Human-Dominated Ecosystems with a Hierarchical Patch Dynamics Approach

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Abstract

Global ecosystem has been intensively modified by human activities. To address the structural and functional complexity of human-dominated terrestrial ecosystem, a hierarchical patch dynamic model (HPDM) that couples the carbon/water/nitrogen processes is developed. Based on the hierarchy theory (Simon 1962; Wu 1999), 7 hierarchical levels, each of which is nested in the higher level, are modeled: plant organ, plant, population, land-cover/ecosystem, land-use, landscape, and region. Structure, dominant processes, and anthropogenic drivers for these subsystems were identified and addressed in the model.

The model was parameterized, validated, and applied to the Phoenix metropolitan area, AZ. Model simulations revealed the spatial patterns of the carbon pools, and estimated the total ecosystem carbon storage to be 16.8 T g (1 T = 10^{12}) in Phoenix. Among Landuse Functional Types (LUFTs), undisturbed desert had the largest C storage. Scenario experiments also highlighted the importance of landcover managements (e.g. irrigating, fertilization) to the carbon balance of desert cities like Phoenix.

Modeling the Hierarchical Structure of land ecosystem (model description)

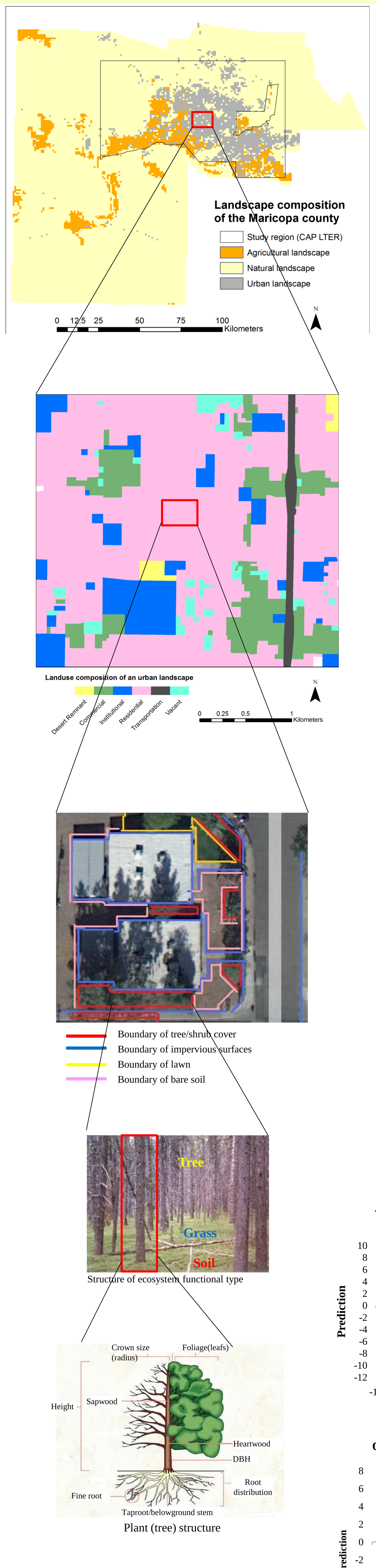
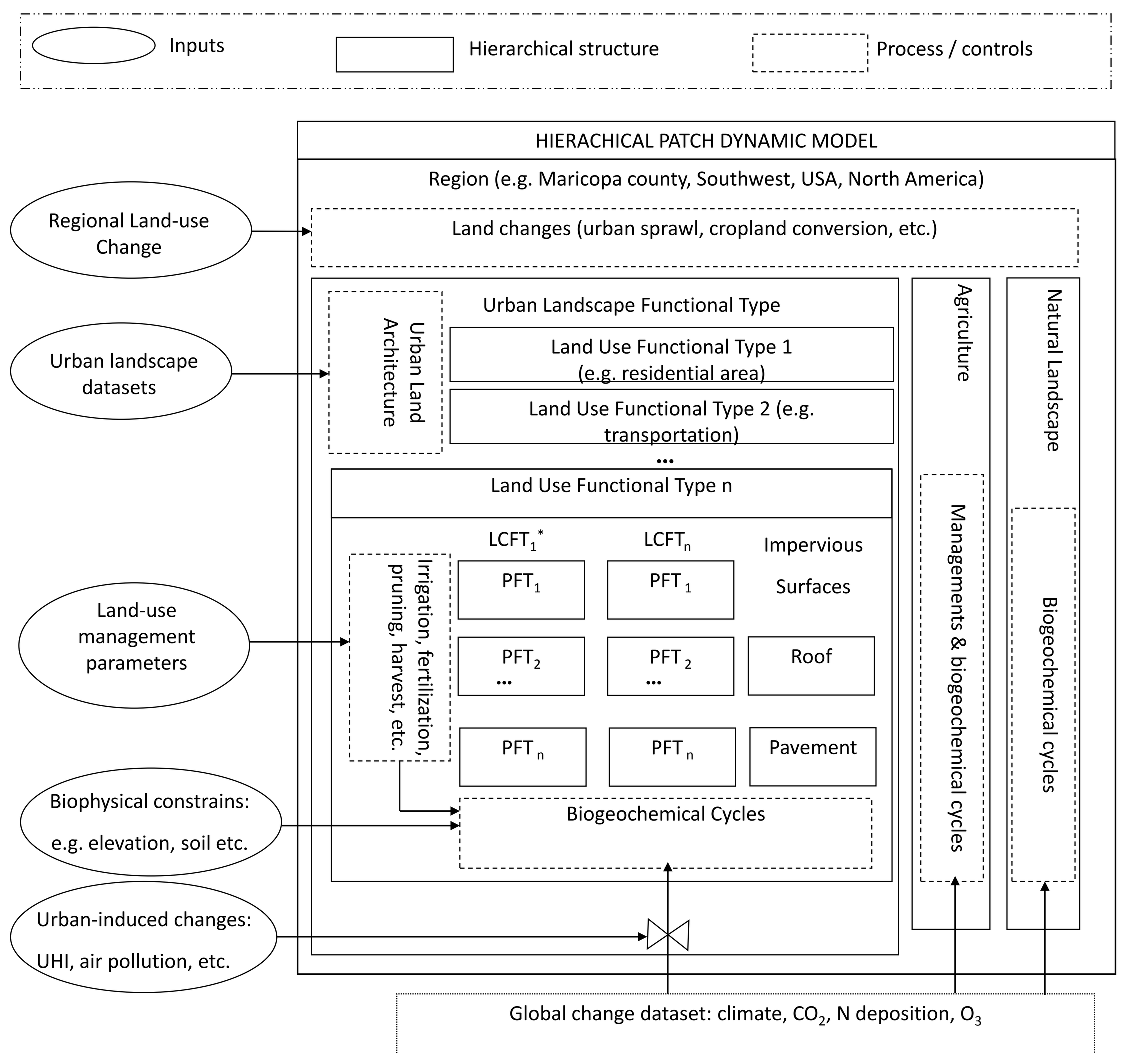


Figure 1, Illustration of the hierarchical structure as modeled by the HPDEM



* LCFT: Land cover functional type; PFT: Plant functional type

(Outputs: Carbon, water, nitrogen fluxes (daily) and pools for each hierarchical level.)

Figure 2, Model structure

Table 1, Description of the hierarchical structure and key processes in the model

Hierarchical Level	Subcomponent	Processes	Interfaces to Anthropogenic Drivers
Region	LSFTs: Urban, agriculture, Natural landscapes	Land-use changes: urbanization, cropland conversion etc.	Land-use changes in response to economic developments
Landscape (LSFT)	LUFTs: Industry, Residential, Urban Ag, Riparian zone	Changes in local climate and atmosphere (e.g. UHI, CO_2 dome, elevated N deposition)	Urban landscape planning, air pollution (related to population & transportation)
Land-use (LUFT)	LCFTs Lawn, Impervious surface, Street tree, Bare soil	LCFT managements (e.g. irrigation, fertilization, pruning)	Management regime (related to the social-economic background of the neighborhood)
Land-cover Functional Type (LCFT) / Ecosystem	PFTs & soil: Broadleaf tree, C4 grass	Resource competition & succession, canopy energy partition; Soil processes, runoff	Microclimate (e.g. cooling effect due to irrigation)
Plant Functional Types (PFTs)	Plant organs : Leaf, root, stem etc.	Growth, allocation, turnover of organs, phenology etc.	Cultivar with modified physiological parameters
Organ	Organic Matter (C, N)	Photosynthesis, respiration, transpiration etc.	

Validation PFTs against Ameri Flux daily NEE (gC/m²) data

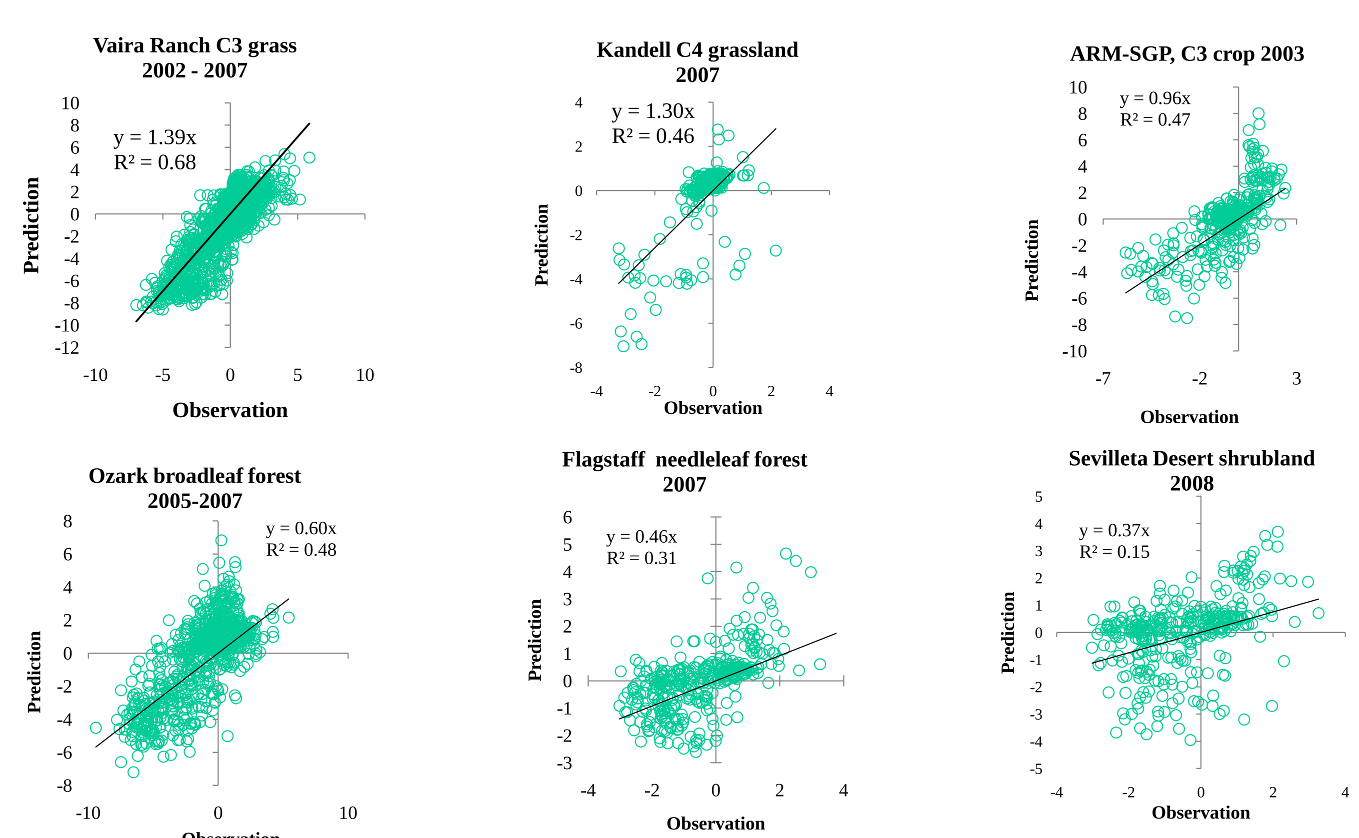


Figure 3 Model validation. **NEE**: Net Ecosystem Exchange (g C/m²/day)

Case study in the Phoenix Metropolitan Area

CAP LTER area: Lat/Lon (33° 26' N 112° 1' W);
Total area (6608 km²);
Dominant vegetation (Desert shrubs);
Annual precipitation (210 mm);
Potential Annual Evaportranspiration (1500 mm);
Temperature (12℃ ~ 34℃)

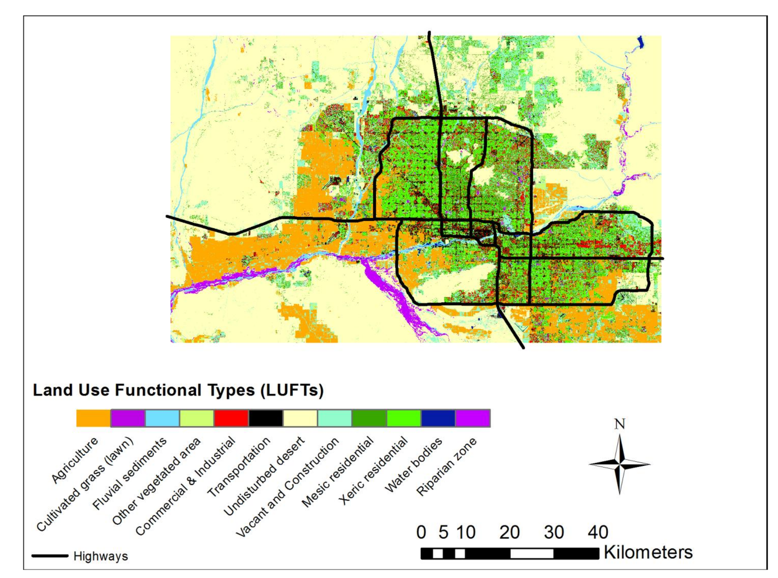


Figure 4, Landscape structure of Phoenix [adapted from Buyantuyev & Wu (2007)]

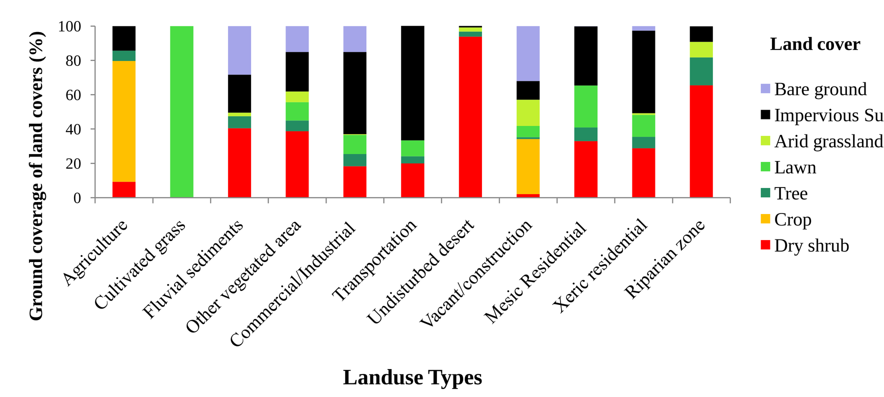
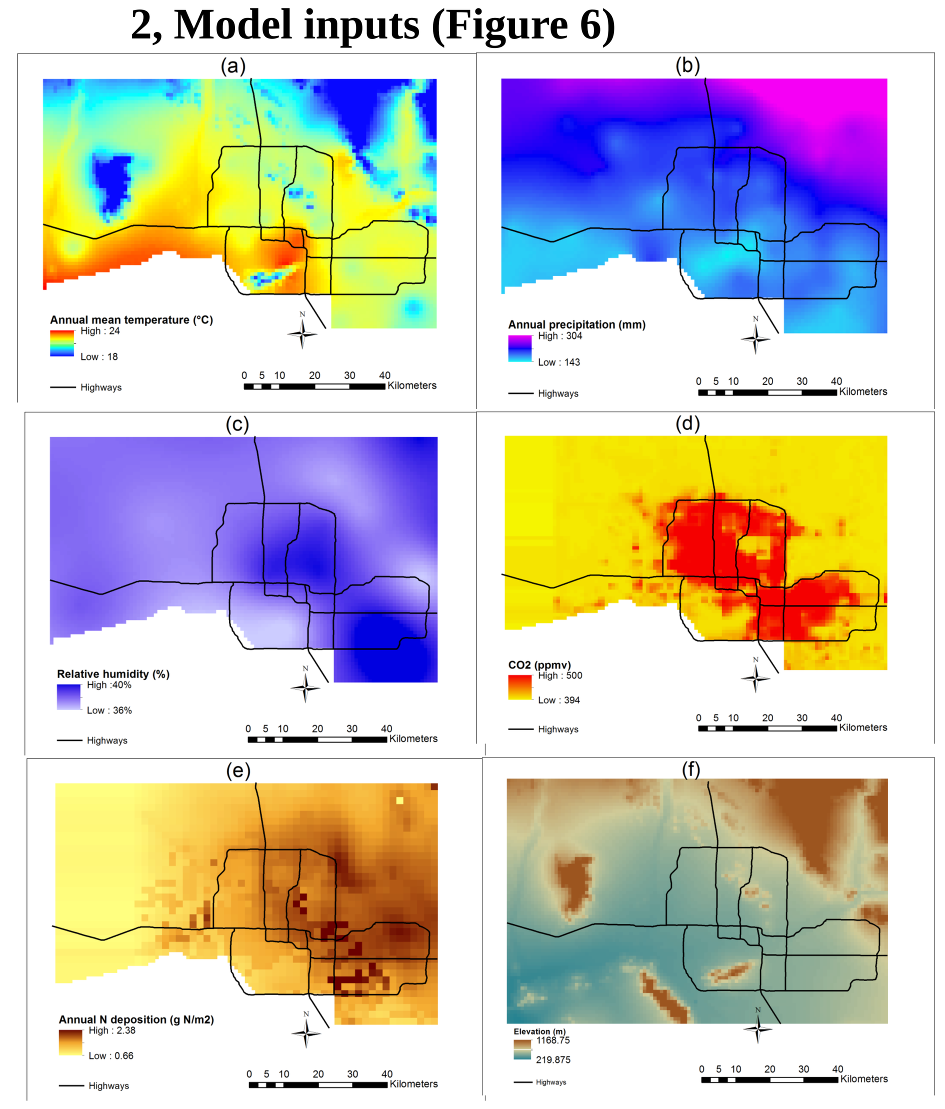


Figure 5, Land cover composition of major LUFTs of Phoenix [CAP LTER 200-survey (Hope, Grimm, et al., 2000-)]

Table 2. Land cover managements

Managements	Treatments	Sources
Fertilization	7.5 gN/m2	Milesi et al (2005)
Irrigated LCFT	Lawn, agriculture, urban trees (only deep root)	
Lawn clipping	Lawn: every 10 days	Survey by Xiaoli Dong
Tree pruning intensity	Calibration, reduce NPP (street tree) by 25%	Stabler and Martin (2004) and Nowak et al. (2002)
Tmax of irrigated lawn	5 Celsius degree cooler than other LCFTs	Hall et al. (2008)
Woody litter treatment	CWD will be pulverized and reapplied to the soil as mulches	Nowak and Crane (2002)

2, Model inputs (Figure 6)



3, Simulation design

Table 3, Scenario design

Spatial resolution: 1 km.
Spatial extent: CAP LTER
Temporal resolution: daily
Temporal extent: 2000 - 2005

Scenarios	Description	Research objectives
s0	CAP LTER 2000 (control scenario)	To quantify C storage of Phoenix ecosystem
s1	Replace Mesic residential -> Xeric residential; Cultivated grass(i.e. golf courses) -> Desert	To investigate the impacts of urban planning (e.g. altering landscape structure to improve water use efficiency) on C
s2	No urban-induced environmental change (CO_2: -16 ppmv, or -4%; N deposition: -0.34 gN/m2/yr, or -33%)	To investigate the impacts of urban-induced environmental changes on urban C balance (e.g. Shen et al. 2008)
s3	No landcover managements (irrigation, fertilization, pruning) (Table 1)	To investigate the impacts of landcover managements on urban C balance

Results and Analysis

Contribution of LUPFs to Phoenix C storage

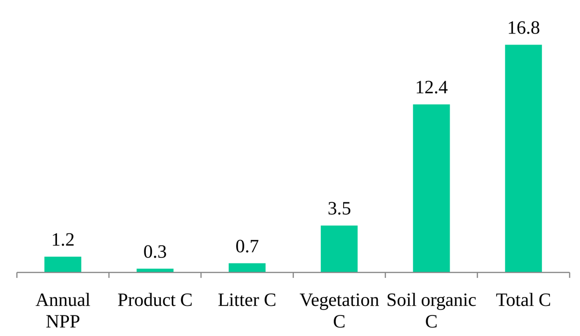


Figure 7, NPP and carbon (C) storage of the Phoenix Metropolitan area (unit: 10^{12} g C).

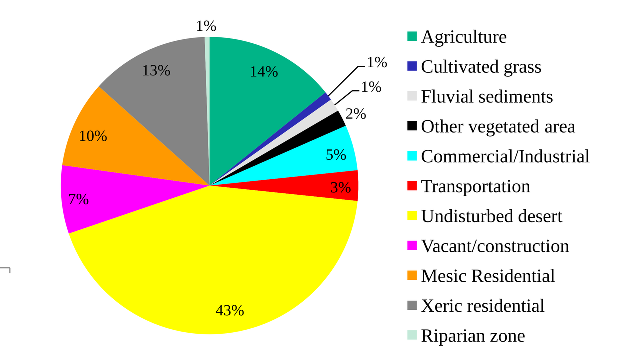


Fig 8. Distribution of carbon storage among landuse functional types.

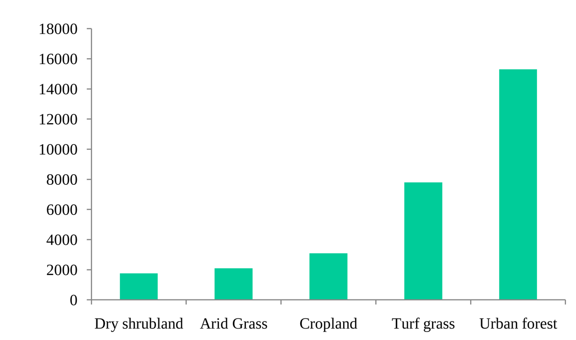


Fig 9. Carbon density of different plant functional types (unit: g C / m²)

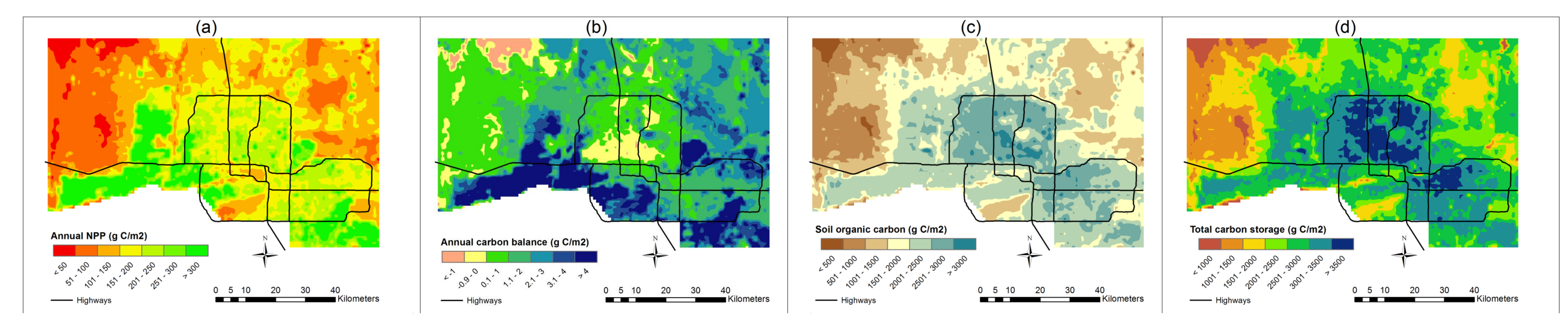
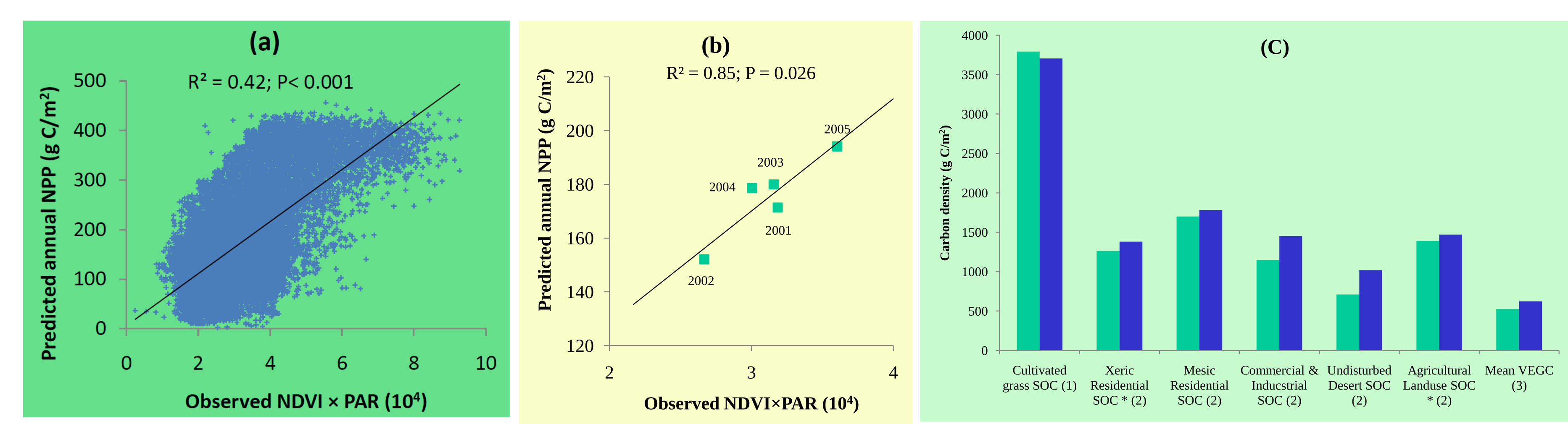


Fig 9. Spatial distribution of NPP and carbon pools. For annual carbon balance, negative value indicates carbon loss in response to climate changes.



* The carbon density of top soil (10 cm) is based on the results of the hierachical bayesian model estimation by Kaye et al. (2008).

Figure 10, Compare model prediction with results from empirical studies. (a) and (b) correlation between model predicted NPP and the annual NDVI x PAR (Buyantuyev and Wu 2009); (c) compare soil organic carbon (SOC) and vegetation carbon (VEGC) against observed carbon density in CAP LTER [data sources: (1) Jenerette et al., 2006; (2) Kaye et al., 2008; (3) Melissa, unpublished data based on the 200-survey].

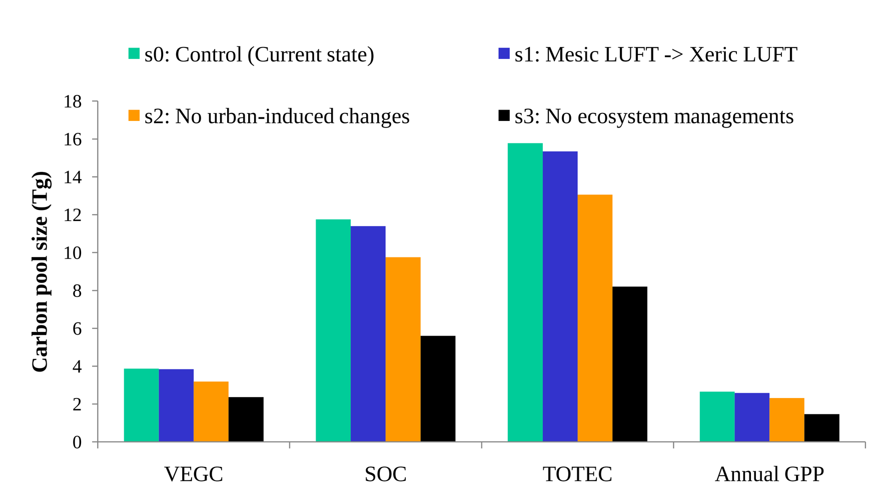


Figure 11, Simulating the impacts of landscape planning, urban-induced environmental changes, and landcover managements on the carbon balance of the Phoenix ecosystems.

Discussion and conclusions:

1, Urban ecosystem (vegetation and soil) accounts for an important share of the total carbon storage in urban as indicated by this study and other studies (Churkina et al. 2009) .

2, The complex landscape structure and interactions among natural environments and human activities require spatial-explicit and process- based approaches/tools (such as the HPDEM) in the urban biogeochemical studies.

3, Our study results is comparable to field observations and the results of remote sensing studies. We found that about 16.8 Tg C was stored in the urban ecosystem of the Phoenix Metropolitan Area, majority of which was stored in the soil. While the desert shrublands accounted for the largest carbon pool size, the urban forest has much higher carbon density.

4, Urban induced environmental changes (elevated CO2 and N deposition) increased carbon storage and productivity of urban vegetations. However, human managements such as irrigation and fertilization have stronger impacts on the carbon balance of the urban ecosystem.

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