Landscape Planning and Biogeochemistry:

Estimating and Analyzing Carbon Sequestration

Efficacy In Dryland Open Space

by

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ABSTRACT

Despite public demand for climate change mitigation and natural open space conservancy, existing political and design efforts are only beginning to address the declining efficacy of the biotic carbon pool (C-pool) to sequester carbon. Advances in understanding of biogeochemical processes have provided methods for estimating carbon embodied in natural open spaces and enhancing carbon sequestration efficacy. In this study, the benefits of carbon embodied in dryland open spaces are determined by estimating carbon flux and analyzing ecological, social, and economic benefits provided by sequestered carbon. Understanding the ecological processes and derived benefits of carbon exchange in dryland open spaces will provide insight into enhancing carbon sequestration efficacy.

Open space carbon is estimated by calculating the amount of carbon sequestration (estimated in Mg C / ha / y) in dryland open space C-pools. Carbon sequestration in dryland open spaces can be summarized in five open space typologies: hydric, mesic, aridic, biomass for energy agriculture, and traditional agriculture. Hydric (wetland) systems receive a significant amount of moisture; mesic (riparian) systems receive a moderate amount of moisture; and aridic (dry) systems receive low amounts of moisture. Biomass for energy production (perennial biomass) and traditional agriculture (annual / traditional biomass) can be more effective carbon sinks if managed appropriately. Impacts of design interventions to the carbon capacity of dryland open space systems are calculated by estimating carbon exchange in existing open space (base case) compared to projections of carbon sequestered in a modified system (prototype design). A demonstration project at the Lower San Pedro River Watershed highlights the potential for enhancing carbon sequestration.

The site-scale demonstration project takes into account a number of limiting factors and opportunities including: availability of water and ability to manipulate its course, existing and potential vegetation, soil types and use of carbon additives, and land-use (particularly agriculture). Specific design challenges to overcome included: restoring perennial water to the Lower San Pedro River, reestablishing hydric and mesic systems, linking fragmented vegetation, and establishing agricultural systems that provide economic opportunities and act as carbon sinks. The prototype design showed enhancing carbon sequestration efficacy by 128-133% is possible with conservative design interventions.

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INTRODUCTION

Overview

The efficacy of the biotic carbon pool (C-pool) -- vegetative mass and microbial processes in soils to a depth of three meters -- to sequester carbon (C) has declined significantly due to human land-use modification, deforestation, open space degradation, and other negative human impacts. “Rates of agricultural expansion and forest harvest between 1860 and 1980 suggest that the world biomass has been reduced by 110 billion Mg C since the Industrial Revolution” (Schlesinger 1997, p147). Human impacts on biomass can be seen in changes to the global carbon cycle and changes to the atmosphere (Schlesinger 1997) due primarily to fossil fuel combustion. The decline in efficacy of the biotic C-pool to sequester carbon, combined with huge increases in fossil fuel use, has resulted in an overburdened atmospheric C-pool. This imbalance of the biogeochemical carbon cycle is further exacerbated by acute climate change (ACC) – the result of fossil fuel combustion and resulting increase of carbon dioxide concentrations in the atmosphere. Public vestment in the desire to mitigate negative climate change due to increasing atmospheric carbon and other greenhouse gasses (GHGs) has rekindled global conservancy efforts (ranging from international to grassroots volunteer efforts). In turn, demand for sustainable technologies and a desire for a built environment that incorporates and protects natural processes have been increasing.

Responding to public demand for sustainable technologies and conservancy of open spaces, ecologists have made significant advances in modeling ecological processes. Despite a growing body of knowledge pertaining to ecological processes and public demand for environmental, social, and economic benefits derived from carbon embodied in open spaces, designers have not yet fully incorporated complex ecological models and promising land management strategies into design processes. Furthermore, designers have not yet adequately described the ecological, social, and economic benefits (in terms of value-added) of carbon and other greenhouse gasses (GHGs) sequestered in natural open spaces (where these gases are essential to natural processes). Overlooked benefits include ”helping tackle greenhouse gas emissions and ecosystem services such as habitat restoration, rural business development and diversification, landscape empowerment, and enhancement of urban areas” (Great Britain Forestry Commission 2011, pg. 3). In particular, the benefits of biotic C-pools are overlooked as carbon reservoirs as evidenced by a long history of negative human land-use, deforestation, and land degradation. Drylands, in particular, where over one third of the human population resides, negative human impacts are intensified.

Despite the potential benefits of including ecological processes in design of the built environment, carbon sequestration efficacy of dryland open spaces is rarely addressed. As with all mature natural open spaces the majority of carbon influx in biotic C-pools quickly effluxes through vegetative and soil respiration. Dryland carbon reservoirs, where naturally high calcium content catalyzes the transformation of soil organic matter (SOM) into soil inorganic carbon (SIC) through lateral carbon transfer from plant roots, natural weathering and leaching processes. Secondary or pedogenic carbonates (one form of SIC) are especially important to a balanced biogeochemical carbon cycle because carbon embodied in secondary carbonates do not easily return (efflux) to atmospheric C-pools.

“Dryland soils contain at least as much or more soil inorganic carbon than soil organic carbon” (Lal 2003, Batjes 1998, Eswaran *et al.* 2000) – making dryland soils (particularly aridisols) effective carbon sinks. Despite the efficiency of dryland systems, degradation and desertification are pervasive and results in sizable emission of carbon dioxide into the atmosphere (Lal 2003). Estimating and analyzing carbon in dryland systems will support conservancy efforts by describing ecological, social, and economic benefits that can be enhanced by design interventions to increase efficacy of carbon sequestration in natural dryland open spaces – the most effective terrestrial carbon sink.

This study investigates methods of estimating and analyzing carbon exchange and capacity of dryland open space C-pools and projecting impacts of design interventions to the efficacy of carbon sequestration in generating social, economic, and environmental benefits. Embodied carbon in an open space system is estimated by calculating the amount of carbon sequestration (typically estimated in Mg C / ha / y). Due to varied studies and goals regarding research into biogeochemical carbon cycles the term “carbon sequestration” has many definitions. In the context of carbon embodied in natural open spaces carbon sequestration is defined as the “uptake of atmospheric carbon dioxide during photosynthesis and the subsequent transfer of some fixed C into vegetation, detritus, and soil pools for secure storage” (Lal and Lorenz 2010, pg. 11).

The demonstration project portion of this study identifies independent variables such as soil type, native vegetation, amount and frequency of water, and human land-use which are analyzed in context to five proposed carbon sequestration vegetative systems (typologies): hydric, mesic, aridic, biomass for energy production, and traditional and modified agriculture. Vegetative systems generally indicate carbon sequestration efficacy -- higher biomass vegetative systems having higher carbon sequestration efficacy due to higher rates of carbon flux through photosynthesis. In this study, open space vegetative systems are referred to simply as systems; vegetative biomass is assumed in the context of biogeochemistry. Hydric (wetland) vegetative systems receive a significant amount of moisture; mesic (riparian) vegetative systems receive a moderate amount of moisture; and aridic (dry) vegetative systems receive low amounts of moisture. Biomass for energy production (perennial biomass) and agriculture (annual / traditional biomass) are effective carbon sinks if managed appropriately. Impacts of design interventions to the capacity of dryland open space C-pools are calculated by estimating carbon sequestered in an existing open space base case compared to projections of carbon sequestered in the modified system. Reduced benefits of carbon sequestration in disturbed and degraded dryland open space highlight the value of conserving and restoring natural open space systems – the most efficient carbon reservoirs.

The demonstration project takes into account a number of site-specific limiting factors and opportunities for a dryland site in the Lower San Pedro River Watershed in the Southwest United States. Variables include: availability of water and ability to manipulate its course, existing and potential vegetation, soil types and use of carbon additives, and land-use (particularly agriculture). Specific design challenges to overcome included: restoring perennial water to the Lower San Pedro River, reestablishing hydric and mesic vegetative systems, linking fragmented vegetation, and establishing agricultural systems that provide economic opportunities and act as carbon sinks. The prototype design showed enhanced carbon sequestration efficacy of 128-133% was attainable over the base case.

Improving communication between ecology and design is important to continual refinement of design processes as well as an important first step toward future conservancy and enhancement of dryland open space. Advances in mapping the carbon biogeochemical cycle suggest a number of design opportunities for enhancing dryland open space ecological, social, and economic benefits. Potential primary benefits of enhancing dryland biotic C-pools through design and management interventions include: increased efficacy of climate change mitigation, improved water quality, increased biodiversity, and opportunities for agricultural biomass; such as energy production, increased yield, and soil carbon reservoirs.

Problem Statement

Opportunities for carbon sequestration in dryland open space C-pools in decline. This decline in carbon sequestration efficacy leads to the need for design interventions. However, the nature and form of potential carbon sequestration is not clearly defined. Is it possible to reverse declines in carbon sequestration efficacy in dryland through design interventions?

Thesis Statement

In the context of carbon flux and sequestration, what are the environmental, social, and economic benefits of carbon embodied in dryland open spaces – can enhanced carbon sequestration efficacy be predicted in dryland open space carbon sinks?

Chapter 2

BACKGROUND: LITERATURE REVIEW

The Carbon Cycle

Carbon is the fourth most common element in the universe by mass (after hydrogen, helium, and oxygen). The atomic properties of the carbon atom allow easily formed, stable bonds with other atoms under varying conditions. Carbon compounds can be gas, liquid, or solid under temperature ranges found on the surface of the Earth (Salati *et al.,* 2010). The characteristics of carbon make possible all organic compounds -- such as long organic chains and rings -- which are essential to life on earth (Salati *et al.,* 2010). "The carbon cycle describes the exchange of carbon atoms between various reservoirs within the earth system" (Salati *et al.,* 2010, p. 156).

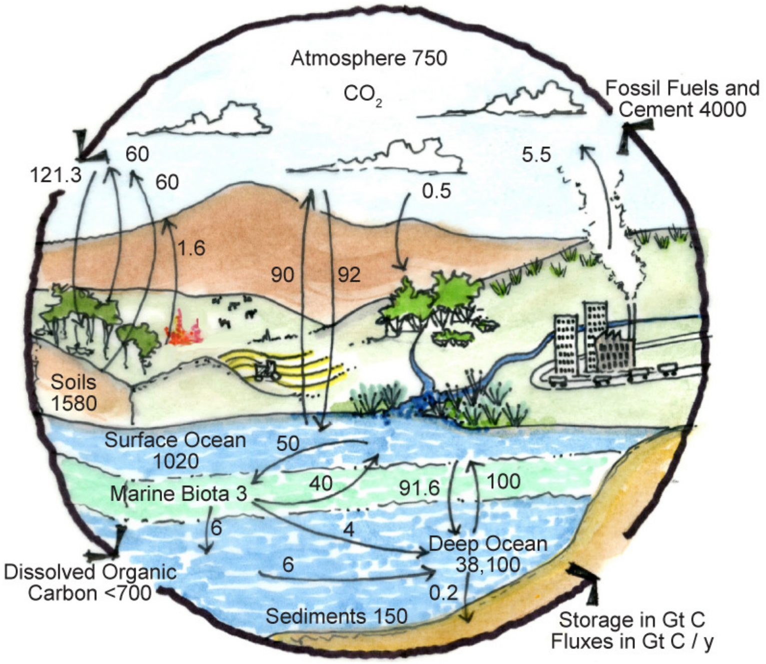


Figure 1. The biogeochemical carbon cycle showing storage and exchanges of carbon between reservoirs (Adapted from the National Aeronautics and Space Administration, 2008).

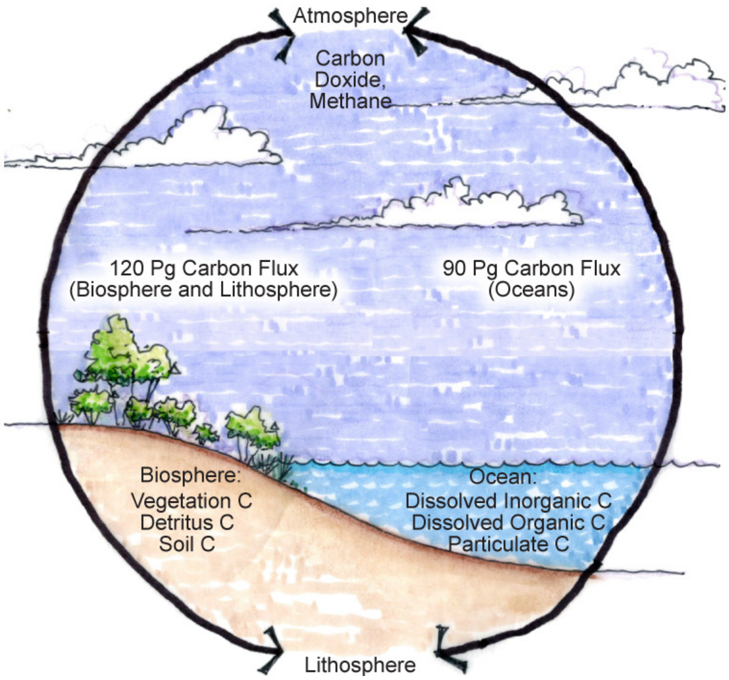


Figure 2. Carbon Flux between atmosphere, biosphere, lithosphere and oceans (adapted from Lorenz and Lal, 2010).

Carbon flux is the exchange of carbon between the biosphere's carbon pools (C-pools), which include the terrestrial biosphere (which includes soils up to one meter depth), lithosphere, hydrosphere, atmosphere, and fossil fuels of the earth (Lal, 2007; Salati *et al.,* 2010). In the context of biogeochemistry and carbon sequestration processes, the biosphere's C-pools are further divided into five principal global C-pools: biotic, pedogenic, oceanic, atmospheric, and geologic (Lal, 2007). The oceanic C-pool, the largest global carbon pool, is estimated at 38,000 Pg C, and carbon efflux (loss) is relatively small (Salati *et al.,* 2010). The atmospheric C-pool, by contrast, contains only about 760 Pg C as carbon dioxide. Exchange between the atmospheric C-pool and oceanic C-pool is skewed. Carbon influx (debits) from the atmospheric C-pool to the oceanic C-pool, through diffusion and aquatic biomass, is substantially larger than carbon efflux (credits) from the oceanic to atmospheric C-pools. This imbalance means, "atmospheric concentration of carbon dioxide is determined by the oceanic C-pool and not the other way around" (Shlesinger, 1997; Salati *et al.,* 2010; Falkowski *et al.,* 2000). "If carbon gain is more than C lost the pool is considered a carbon "sink", on the contrary it is considered a carbon source" (Salati *et al.,* 2010, p. 156).

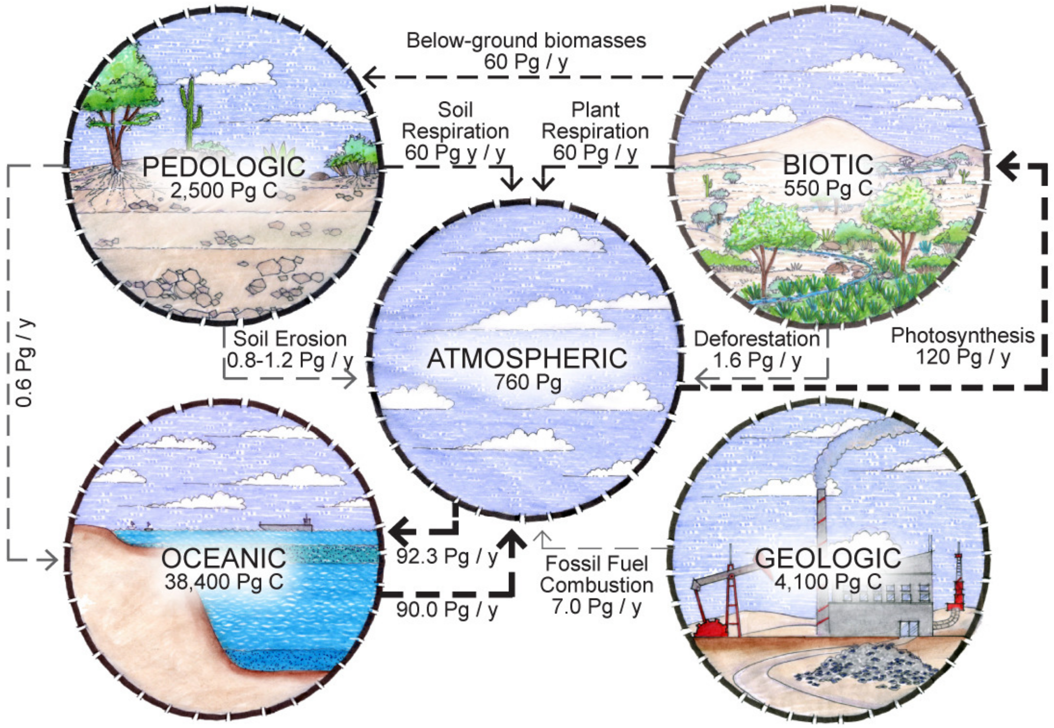


Figure 3. Carbon exchanges between atmospheric, biotic, pedologic, oceanic, and geologic carbon pools (adapted from Salati *et al.*, 2010*).*

The biogeochemical carbon cycle describes the exchange of carbon involving the biotic C-pool. The largest amount of natural carbon exchange occurs between the atmosphere, biotic, and pedogenic C-pools. Carbon naturally cycles from the atmosphere to the biotic C-Pool through photosynthesis where it is utilized as a fundamental building block for life. The biotic C-pool -- or vegetative carbon -- includes aboveground biomass (shoot), underground biomass (root), and necromass (Salati *et al.,* 2010). The pedogenic C-pool -- soil up to 1 meter depth -- is comprised of soil organic carbon (SOC) and soil inorganic carbon (SIC). The SOC-pool includes carbon contained within plants (roots), detritus, animals, microorganisms, and microbes; the SIC-pool consists of elemental C, calcium carbonate minerals (limestone) and dolomite (Salati *et al.,* 2010). The geologic C-Pool has the distinction of once being a relatively stable (low flux) C-pool that is now, due to human use, the largest burden to the carbon cycle (approximately 7 Pg C annually is credited to the atmosphere through fossil fuel combustion) (Salati *et al.,* 2010). The geologic C-pool is comprised of gas, oil, and coal is estimated to be 4,100 Pg C -- larger than biotic, pedogenic, and atmospheric C-pools combined (Lal, 2007). Coal and oil represent approximately 40% of global carbon dioxide emissions (Salati *et al.,* 2010, p. 156).

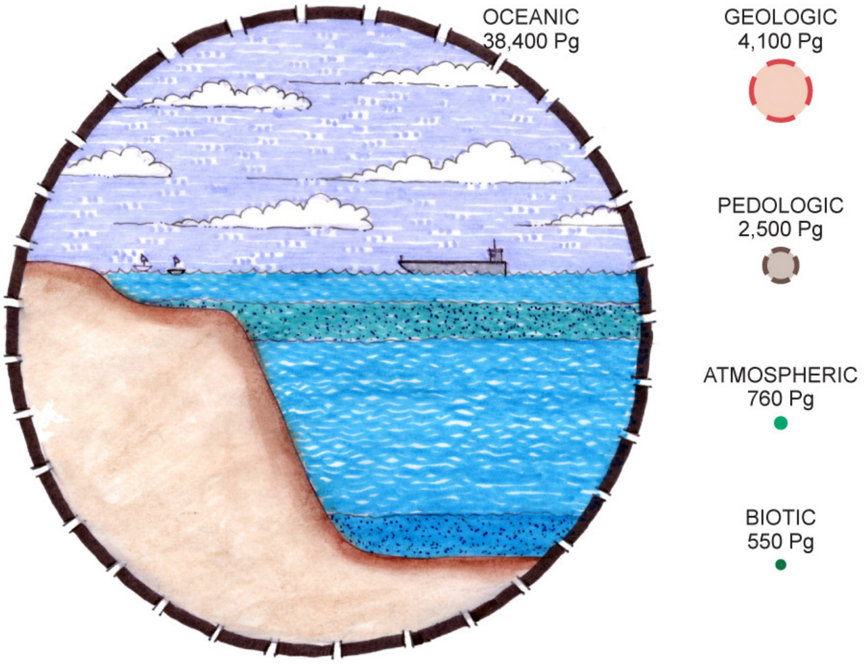
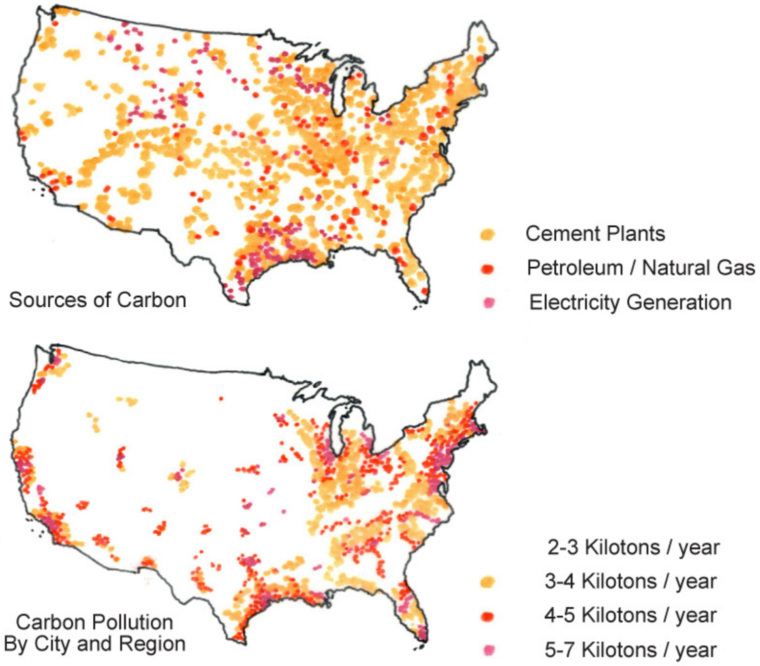


Figure 4. Proportional diagram showing the size of the ocean carbon pool compared to the geologic, pedologic, atmospheric, and biotic carbon pools.

The Carbon Cycle and Human Impacts

Negative human impacts such as fossil fuels combustion and associated carbon dioxide emissions, mining, deforestation, and landscape degradation (including desertification in dryland ecosystems) have severely disrupted the natural carbon cycle. Combustion of fossil fuels releases an estimated 7 Pg C into the atmosphere each year (Salati *et al.,* 2010). Carbon dioxide concentrations in the atmosphere have risen from about 270 parts per million (0.026%) before the industrial age to about 380 parts per million (0.038%) by 2006, a 41% increase over pre-industrial values, and a 31% increase since 1870 (Schlesinger, 1997).



Sources of Carbon

Carbon Pollution
By City and Region

Figure 5. Continental United States carbon efflux by source and city and region (adapted from NETL, 2010).

Atmospheric carbon dioxide is increasing as fossil fuel combustion continues to increasingly exceed the rate at which natural components of biogeochemical system can take up carbon and buffer climate change (Schlesinger, 1997). Restoring and preserving natural biogeochemical processes are particularly in dryland open spaces due to large global potential of carbon sequestration in dryland ecosystems. Dryland regions cover about 47.2% of terrestrial land area or about 6.15 billion hectares (Lal, 2007). 5.6% of the terrestrial land area in North American alone is dryland (Middleton and Thomas, 1992; Noin and Clarke, 1997; Reynolds and Smith, 2002; and Lal, 2003).

Unfortunately, carbon overburden influences radiation balance and is a major cause of acute climate change (ACC), which further impairs natural biogeochemical processes and biodiversity (Schlesinger, 1997). ACC is attributed primarily to fossil fuel combustion, deforestation, human land-use conversion, and open space degradation (particularly desertification). Oxidation of carbon from disturbed biotic C-pools contribute significantly to concentrations of carbon dioxide and other GHGs in the atmosphere. Carbon dioxide and other GHGs in turn trap and reflect infrared energy (heat). Already, “Carbon dioxide concentrations [in the] atmosphere has [*sic*] increased by 30 percent since the industrial era” (Salati *et al.,* 2010; Intergovernmental Panel on Climate Change, 2001). Infrared radiation causes oceanic warming which is most apparent at the North and South poles where net loss of infrared radiation relative to incident sunlight occurs (Schlesinger, 1997). Oceanic C-pools regulate (buffer) atmospheric carbon dioxide concentrations and reduce the impacts of increased infrared radiation. While satellite measurements are inconclusive, worldwide weather station readings suggest that there is already increasing evidence that oceanic buffers are close to saturation and that rising carbon dioxide concentrations will increase at faster rates (Schlesinger, 1997). A side effect of global oceanic warming is an acceleration of the hydric cycle through greater evaporation rates. Greater water vapor (clouds) further accelerates capture of reflected infrared heat (Schlesinger, 1997). It is the increased abundance of clouds and tropospheric aerosols -- the result of rising infrared heat and albedo -- that confound climate models as increasing cloud cover slows acute climate change (Schlesinger, 1997).

Human impacts to the carbon cycle are accelerating precipitation events and evapotranspiration; creating a hotter and more humid planet (Schlesinger, 1997). Already sea levels have been altered, crop yields have been reduced, biodiversity has sharply declined, and climate is disrupted evidenced by increasing frequency of *El Niño* and *La Niña* events (unusually warm and cool oceanic temperatures), rapid decline of polar ice caps, and extensive droughts in equatorial rainforests. These impacts increase the intensity and frequency of natural disasters such as tornadoes, hurricanes, floods, and droughts (Lelieveld, 2006). Development of more efficient transportation, manufacturing, and building processes are only part of the solution to reduce carbon dioxide emissions; alternate energy and sequestration of carbon must also be considered or the carbon cycle will continue to deteriorate.

Carbon Mitigation Advocacy

Human impacts to the environment have generated international, U.S. government, and volunteer responses. The United Nations Framework Convention on Climate Change (UNFCCC or FCCC) in 1997 encouraged industrialized countries to stabilize GHG emissions. Later, the Kyoto Protocol set binding targets for 37 industrialized countries and the European community for reducing GHGs. The Kyoto Protocols focused on cutting emissions but have been only partially successful Member countries struggle to meet projected emission cuts and the United States declined to participate altogether despite being the top producer of GHGs emissions at the time. Total U.S. GHG emissions were 6.64 Pg of carbon dioxide equivalents in 2009 alone (U.S. Environmental Protection Agency, 2011). Though largely ineffective at reducing GHG emissions major lessons were learned from applying the Kyoto Protocols: international regulation is possible and trading GHG emission credits is largely ineffective. Lack of emissions estimating and tracking mechanisms severely reduced the efficacy of carbon emission trade systems (carbon markets) (U.S. Congressional Budget Office, 2009). The International Panel on Climate Change (IPCC) has expressed concerns over carbon markets established by the Kyoto Protocol due to lackluster results; it is increasingly likely that all nations that agreed to meet the Kyoto Protocol goals will not meet goals in the allotted amount of time (IPCC, 2007).

In response to renewed global attempts to curb climate change, Brazil pledged to reduce carbon emissions by 40% by 2020 (Inter-ministerial Committee on Climate Change, 2007). Brazil's commitment -- a deviation from the Kyoto Protocol strategy revolving around carbon markets -- reduced carbon dioxide emissions directly by curtailing deforestation of the Amazon Rainforest – the largest terrestrial biomass. It is no coincidence that The Brazil National Climate Policy was timed to put pressure on industrialized countries ahead of global discussions at the UNCCC Annual Meeting (commonly referred to as the

Copenhagen Summit) in December 2009. The proposed Copenhagen Climate Treaty (presented at the Summit) expanded on lessons learned from the Kyoto Protocols and followed Brazil's example in advocating direct regulations to curb GHG emissions. The Copenhagen Climate Treat continued to refine climate change mitigation through emission markets but additional goals included: reducing global deforestation by 75% by 2020, requiring industrialized nations to peak emissions by 2020, and radically reduce using of fossil fuels (IPCC, 2009). The Copenhagen Climate Treaty was abandoned and the binding Copenhagen Accord, drafted by the US, China, India, South Africa, an Brazil, simply recognized that "deep cuts in global emissions are required according to science" but did little to advance efforts to regulate negative human impacts to atmosphere (IPCC, 2009). The lofty goals of the Copenhagen Summit were abandoned in favor of less binding agreements under United States-led pressure (UNFCCC, 2010). More recent international goals discussed at the UNFCC 2011 Annual Meeting in Cancun, Mexico in 2011, once again proposed strong regulation: setting reduction targets for developed countries, further specifying decisions under the Kyoto Protocol, developing mitigation plans in developing countries, reducing emissions through stronger actions on forests, and advancing cost-effective means to achieve mitigation goals (UNFCCC, 2011).

Despite international engagement in curbing emissions and mitigating negative climate change, specific and significant regulatory policies have yet to be established at a national-scale in the United States according to the U.S. Congressional Budget Office (U.S. CBO, 2009). The recent United States Senate [Carbon] Cap-and-Trade Bill establishing a new commodity -- the right to emit carbon dioxide – passed in the House of Representatives by a narrow margin –

219 to 212 (U.S. CBO 2009). Language in the Cap-and-Trade bill did not reflect lessons learned from the inefficiencies of the 1997 Kyoto Protocol; namely the difficulties of tracking carbon credits and debits.

Carbon emission markets allowances would have resulted in the reallocation of substantial value - roughly 145 billion dollars annually (CBO 2009). Unfortunately, reflecting the U.S. Government's tendency to support incentives rather than direct regulation, revenues were slated to offset economic impacts rather than directly mitigate negative human impacts to the carbon cycle. Economic incentives took a wide range for forms -- most having nothing to do with reducing carbon emissions. Incentives included rebates to individual households, allowances to key businesses (energy producers and buyers/distributors), reduction to income tax rates, payroll tax rates, income tax rebates, expansion of the earned Income tax credit, supplements to the Supplemental Nutrition Assistance Program (SNAP), increased funding for the Low-Income Home Energy Assistance Program, and increases to Social Security (U.S. CBO, 2009). Only a small portion of the market-generated funds directly contributed to carbon emission mitigation in the form of research projects. Research funds were to be focused on reducing economic impacts associated with the carbon markets and developing energy generation savings technologies (U.S. CBO, 2009). The relatively weak Cap-and-Trade Bill was never implemented nor are politicians introducing more effective bills as of 2011.

As a result of U.S. government policy lagging behind public sentiment regarding the environment, a massive volunteer movement has resulted in the United States. While a national "green" movement has resulted in increasing individual and grassroots engagement in environmental movements, carbon emissions are so massive that individual contributions have little overall impact on total emissions in the United States. Emissions have increased 7.4 percent from 1990 to 2009 (U.S. EPA, 2011) despite national efforts. The United States building industry, responding to market demand, and negligible national response has developed a number of volunteer standards.

The most established is the United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED). According to the USGBC, LEED is "an attempt to improve environmental quality of buildings and their impact on the environment and is consensus-based, market-driven, and a balance between existing and innovative practices" (USGBC, 2010). The LEED systems (New Construction, Existing Buildings: Operations and Maintenance, Commercial Interiors, Core and Shell, Schools, Retail, Healthcare, Homes, and Neighborhood Development) take into account reduction in emissions, reduction in energy U.S., and preservation of open spaces in association with buildings. However, The LEED systems have a limited scope (despite efforts to be more holistic); standards are narrowly focused on individual buildings and sites. As a volunteer/brand response to promote more efficient and healthier buildings the LEED program has encouraged innovation. Unfortunately, LEED has yet to generate global-scale (or even national-scale) emission reductions required to stabilize and reduce carbon emissions and strain on the biogeochemical carbon cycle.

The American Society of Landscape Architecture's (ASLA) Sustainable Sites Initiative (SITES) is a direct response to the inefficiencies of the LEED system. SITES, like LEED, is a volunteer/brand response to negative climate change and seeks to maintain "balance of atmospheric gases at historic levels, creating breathable air, and sequestering greenhouse gases" (SITES, 2009). The Sustainable Sites Initiative also promotes air cleansing by encouraging the removal/reduction of pollutants in the air and fostering environmental stewardship in land development and management though the specifics of how they hope to accomplish this are still being considered. Originally carbon sequestration was directly addressed -- points were received for "storing carbon as organic matter" and lowering overall carbon output -- though these provisions were removed from subsequent versions (SITES, 2009). Ideally, once methods for estimating and analyzing carbon exchange and reservoirs are established, a carbon sequestration section will be incorporated into future SITES versions.

In 2009, land-use, land-use change, the development of forest carbon sinks, biomass for energy and wood production were credited with offsetting nearly 1.4 Pg C annually in the United States alone; nearly one-fifth of total annual U.S. carbon dioxide emissions (U.S. EPA, 2011). The Environmental Protection Agency (EPA), responsible for developing the Greenhouse Gas Inventory (GHG Inventory), claimed, "greenhouse gas emissions are partly offset by C sequestration in managed forests, trees in urban areas, trees in urban areas, agricultural soils, and land filled yard trimmings – estimated offsets of 15.3% of total emissions in 2009" (U.S. EPA, 2011, § 2, p. 3). Based on these numbers total emissions in the U.S. may be offset by local projects and that carbon equilibrium is an attainable goal if total emissions peak and are reduced.

Chapter 3

BACKGROUND: CARBON SEQUESTRATION

Principal Industrial Carbon Sinks

There are many innovative artificial processes (including a number of expensive chemical processes) for sequestering carbon from our atmosphere and balancing the overburdened natural carbon cycle. Due to massive amounts of carbon being produced (for energy, cement, and transportation being the three largest producers of carbon in the United States) industrial-scale solutions are being considered. The environmental impacts of artificial carbon sequestration are potentially catastrophic though there is tremendous potential to reduce the atmospheric C-pool and offset fossil fuel emissions through industrial-scale carbon sinks. Principal processes being considered include: soil injections (such as biochar and coal fly ash), deep saline injections, oceanic iron fertilization, oceanic basalt storage, industrial reuse, and cloud seeding.

Increasing the use of coal fly ash can result in significant debits from the atmospheric C-pool. Coal fly ash is a by-product of coal combustion for energy production; coal fly ash is a gray, powdery, material that is left over after coal is burned and accumulated from the air through pollution control filters (required in the U.S. and Europe for all coal-fire plants). Coal fly ash has been used as a supplement for agriculture soils for as long as coal has been burned for fuel. Coal fly ash addresses nutrient depletion in soils and is available in large quantities near coal burning power plants. Coal fly ash is also utilized as an additive for cement (along with glass fiber) for building materials. Like mature vegetated open spaced, carbon sequestered in soils reach a steady state (after approximately 40 years). Carbon in excess of carbon equilibrium oxidizes and is credited to the atmosphere as carbon dioxide. Coal fly ash often contains heavy metals that are hazardous to humans and wildlife (particularly fish) and can cause long-term environmental harm. Metals found in coal fly ash include: arsenic, beryllium, cadmium, chromium, lead, selenium, thallium, and vanadium, which can seep into ground water (Luther, 2010). New technologies for separating heavy metals from coal fly ash may utilizing this industrial byproduct safer for the environment and for agricultural use but also more expensive.

Another soil additive, biochar, is an ancient practice that converts agricultural waste into a soil enhancer that sequesters carbon, boosts food security (with more consistent and larger crop yields), and discourages deforestation. Like coal fly ash, biochar is utilized as a soil additive with the significant additional benefit over coal fly ash that biochar contains no heavy metal residues. The International Biochar Initiative (IBI) estimates that biochar soil amendments can be used to sequester 2.2 Pg C annually (approximately one third of the total human production of carbon) through direct sequestration in soils as soil additive to open space (IBI, 2009). Additionally, biomass is easily accountable and locally available. Biochar has particular relevance in areas with low carbon tropical soils where biochar as an additive prevents deforestation for agriculture (Steiner, 2006).

Carbon influx (debits) from the atmospheric C-pool to the oceanic C-pool, through diffusion and aquatic biomass, is substantially larger than carbon efflux (credits) from the oceanic to atmospheric C-pools. This imbalance means that atmospheric concentration of carbon dioxide is determined by the oceanic C-pool and not the other way around (Schlesinger 1997; Salati *et al.*, 2010; Falkowski *et al.*, 2000). This imbalance also means that there is tremendous potential to artificially increase oceanic carbon through additives. One such additive is iron, which has been shown “to play a critical role in [oceanic] nutrient utilization” (Coale 2009, p. 1) and when it is added to large quantities to the aquatic systems, added nutrients catalyze rapid growth. Ocean iron fertilization is an industrial-scale process that capitalizes on the nutrient demand of phytoplankton in oceans (approximately 92 Pg C is debited from the atmosphere by aquatic biomass annually) (Salati *et al.*, 2010). Iron naturally plays a part in the biogeochemical carbon cycle where carbon and iron are bonded through chemical reactions to form secondary carbonates. An explosion in the growth of phytoplankton results in rapid uptake of carbon from the atmosphere via photosynthesis (Coale, 2009). The growth of phytoplankton is unsustainable; massive oxygen uptake during photosynthesis depletes suspended oxygen and results in massive die-offs of phytoplankton and all creatures that venture into “dead zones” (Coale, 2009). Dead phytoplankton and any creatures that perish due to lack of oxygen in oxygen-depleted “dead-zones” fall to the ocean floor in such numbers that the phenomena is called “marine snow”. Carbon embodied in marine snow is transferred to the ocean floor where carbon reaches a stable state under high pressure and cold temperatures. Furthermore, sequestration of carbon dioxide would “change the pH of the entire ocean and small perturbations in carbon dioxide or pH may have adverse effects for the ecology of deep-sea biota and for the global biogeochemical cycles” (Seibel and Walsh, 2001; Salati *et al.*, p. 157). Oceanic iron fertilization is especially devastating to ocean habitat, as substantial carbon sequestration would require the seeding of large swaths of ocean.

“Another technique [of industrial-scale carbon sequestration] is the injection of industrial carbon dioxide into deep geological strata” (Salati *et al*., p. 157). Ocean basalt columns are rich in iron and magnesium, which easily reacts with carbon; extrusions of molten basalt along volcanic ridges in cold seawater create voids where carbon dioxide can be injected for storage at high pressure and low temperatures. While carbon can be efficiently stored in ocean depths, a single leak can catalyze the growth of phytoplankton and subsequent dead zones and marine snow (similar to the impacts of ocean iron fertilization) in local ecosystems. Despite potential environmental impacts, the United States has already identified 78,000 km^2 off the coast of California, Oregon, and Washington that is ideal for ocean basalt storage (Goldberg *et al.,* 2009). Despite potential risks, injections of carbon dioxide into basalt columns along U.S. Coasts are likely to proceed despite potential risks. “It’s clear that the cost and leakage of oceans and geological sequestration are principal issue[s] to overcome (Coale 2009, pg. 1). Large investments are continuing to be made for ongoing research, development of leak-prevention technologies, and development of management practices.

Industrial reuse of carbon dioxide is required in the United States and Europe and new processes for reuse are being developed. Industrial-scale manufacturing and energy production are the primary sources of carbon dioxide emissions. The benefits of reuse of carbon for industry are that carbon dioxide is readily available and can be captured as its source instead of after it has been released into the atmosphere. Currently, the primary form of industrial reuse is pre-consumer recycling – for example chipboard, plywood, and hardboard are examples of products whose byproducts and recycling can benefit industrial processes. Both pre-consumer and post-consumer recycling of wood and glass can result in significant reductions in consumer carbon-energy footprints.

"Holding global warming steady at its current rate would require a worldwide 60-80% cut in emissions, and it would still take decades for the atmospheric concentration of carbon dioxide to stabilize" (Victor *et al.,* 2009, pg 3). With negative impacts of acute climate change on the rise drastic measures for reducing atmospheric carbon are being seriously considered. For example, Sulfur cloud seeding, to reduce infrared absorbing GHGs, has also been suggested to reduce atmospheric C-pools. Utilizing existing military fighter and tanker aircraft "injections of sulfate aerosol precursors into the stratosphere has been suggested as a means of geoengineering to cool the planet and reduce global warming" (Robock *et al.,* 2009, pg 1). Sulfur forms natural bonds with carbon dioxide, forming natural biogenic compounds found in biomasses such as: dimethylsulfide and carbonyl sulfide (Schlesinger, 1997). Natural open space systems offset only a small amount of these biogenic compounds. The negative impacts of sulfur cloud seeding and other geoengineering processes are potentially catastrophic to the environment. Alternate carbon sequestration methods, such as conserving, developing, and enhancing natural open space carbon sinks, show significant potential to balance carbon emissions without negative impacts to the environment.

Principal Natural Open Space Carbon Sinks

Natural open space carbon sinks are tremendously effective at removing carbon dioxide from the atmosphere through photosynthesis (hence, "bio" in biogeochemical carbon cycle). While traditional agriculture, deforestation, land degradation, and other negative human land-use reduces efficacy of open space to sequester carbon. Modified land management practices, increased conservation efforts, and afforestation can be promoted to buffer carbon dioxide emissions. The terrestrial C-pool (both biotic and pedogenic C-pools) are "strongly linked to the atmosphere" – 120 Pg C are exchanged annually (Salati *et al.*, 2010, p. 156). Natural open spaces are especially efficient sequesters of carbon -- capturing carbon dioxide through photosynthesis and transferring directly to soils through litterfall and lateral root transfer. Therefore, enhancing natural open space C sinks can increase efficacy of carbon sequestration associated benefits such as: climate change mitigation, improved water quality, increased biodiversity, and opportunities for nontraditional agricultural practices. The Kyoto Protocols and subsequent climate advocacy widely recognize natural open spaces as effective carbon sinks (IPCC, 2007).

Open space systems vary widely based on mean annual biotemperature (average temperature sans values below 0ºC or above 30ºC), total annual precipitation, and the ration of mean annual potential evapotranspiration to mean total annual precipitation (Holdridge, 1947). In the context of carbon sequestration, principal natural open space systems in regards to carbon sequestration are rainforests, temperate forests, mangroves, wetlands, grasslands, and drylands. Rainforests, the largest terrestrial biomass, sequesters substantial amounts of carbon dioxide. Rainforest open space provides a little over 0.22 Mg C / ha / y sequestration where the majority of carbon is not sequestered in soils but in aboveground biomass (U.S. EPA, 2009). Deforestation in rainforests is particularly devastating to the carbon cycle making Brazil's pledge to reduce deforestation especially effective. Drought events and deforestation of tropical rainforests is responsible for approximately 20% of the worldwide annual carbon dioxide emissions (U.S. EPA, 2009).

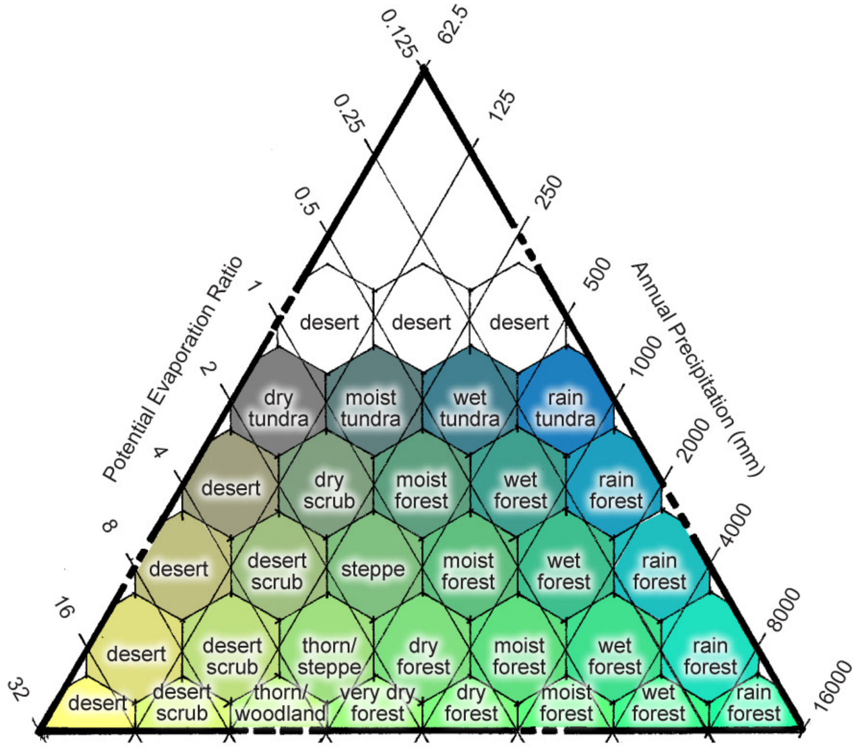


Figure 6. Holdridge Life Zones schematically show land areas based on soils, vegetation, and climactic conditions (Holdridge, 1947).

“Forests occupy about 33% of the land area of the United States and are estimated to contain approximately 71 Pg C” (Kimble *et al.,* 2003, p. 44). Temperate forests contain the most amount of naturally sequestered carbon in the United States. Efficacy of carbon sequestration in the U.S. is in decline due to land-use change and deforestation (Kimble *et al.,* 2003). There are many temperate forests in the United States -- the Tongass, Yellowstone, and Shawnee forests are some of the largest temperate forests in the U.S. With additional management and protection, according to the National Energy Technology Lab (NETL) – U.S. forests are ideal for terrestrial carbon sequestration (NETL, 2009). An increase "of only 0.05% in soil carbon density would mean a total increase of 181 Mg C" in annual carbon capacity (Kimble *et al.,* 2003, p. 44).

Mangroves are severely impacted in the United States -- though fragile mangroves still exist in the Americas in the Caribbean and Mexico. Mangroves are unique carbon sequestration systems in that soil and root respiration of carbon dioxide is directly dissolved and transferred to aquatic C-pools. "The mangrove ecosystem in many wet tropical areas represents one of the most, if not the most productive of natural ecosystems" (Eong, 1993, p. 1). Like rainforests, mangroves are extremely susceptible to acute climate change and human impacts and can become carbon sources. Loss and degradation of mangrove open spaces will result "in the release (from about 1,000 years accumulated mangrove sediments) of some 70 Mg C / ha / y to the atmosphere over a 10-year period – 50 times the sequestering rate" (Eong, 1993, p. 1).

Wetlands are prevalent in the United States and Canada, which have over 25% of the world's wetlands. "Globally, wetlands, while only 4% of the total world land surface area, actually hold 33% of the world's terrestrial carbon" [in soil sinks] (Gleason and Euliss, 1998, pg 3). Marshes (wet grasslands) are the largest terrestrial carbon sinks in the Northern Hemisphere (NETL, 2009). Like mangroves, wetlands transfer of carbon is substantial and wetlands transfer carbon directly to aquatic C-Pools. The 1997 Kyoto Summit was called to action by Canada and acknowledged that wetlands are threatened by global climate change. The Kyoto Protocol was altered to include specific language about wetlands preservation. Canada's commitment to the Kyoto Protocol stated that cut emissions would be met both by direct reduction of total GHG emissions and by preservation of existing wetlands; this resulted in an update to the emissions-focused 1997 Kyoto Protocol (Van der Kamp and Garth, 2011). The largest wetlands found in the United States are located in the Mississippi Delta and Everglades. Wetlands occupy 14% of Canada's land surface, about 1,300,000 km^2, an area slightly larger than the entire province of Ontario (Environment Canada, 2004). Conservancy of existing wetland open space carbon sinks reduces debits from the biotic C-pool to the atmosphere.

Grassland soil systems make ideal carbon sinks due to fine, coarse soils and clay-rich soils. Large grasslands can be found throughout the United States Midwest and include the large Great Plains Grasslands and Tallgrass Grasslands ecosystem. Carbon sequestration in aboveground grassland biomass not a long-term carbon reservoir due to natural burning cycles required for healthy grasslands. Natural burning events account for 1.5 Pg C credit to the atmospheric C-Pool annually (Salati *et al.,* 2010). Ongoing research into the microbial processes of grasslands ecosystems may reveal a way to concentrate carbon dioxide and nitrogen in clay soils. Carbon sequestration in grassland soils may potentially be even more effective long-term carbon reservoirs in the future. "Grassland restoration increased the potential for C sequestration in coarse and fine-textured soils compared to nearby agricultural soils" (Brye and Kucharik, 2003, p. 1).

Natural dryland open spaces are often perceived to be inefficient biotic systems for carbon sequestration due to low net primary production. Calcium-rich dryland soils actually sequester significant amounts of carbon; increasing carbon stored in dryland soils (through afforestation, halting desertification, conservancy of existing drylands, and restoration). Furthermore, global potential of carbon sequestration in dryland soils and biomass is large – dryland regions cover approximately 47.2% of terrestrial land area or about 6.15 billion hectares (Lal, 2010). 5.6% of the terrestrial land area in North American alone is dryland (Middleton and Thomas, 1992; Noin and Clarke, 1997; Reynolds and Smith, 2002; and Lal, 2003). Desert plant materials process as much carbon dioxide at night as temperate forests, which is efficiently stored in high alkaline soils (Smith *et al.,* 2008). For example, tentative calculations based on land area multiplied by improved land-uses [afforestation with Mesquite (*Prosopis spp.)* and Thorntrees (*Acacia spp.)* species in dryland open spaces of the United States Southwest for example] would lead to significant carbon sequestration potential (Lal, 2003). Some desert plant materials, such as the Arizona Desert-thorn (*Lycium exsertum)*, has been recorded as processing carbon dioxide at 120% average temperate forest efficiency (Koyama *et al.,* 2008). Biomasses in dryland systems do not become seasonal carbon sources in winter and warm weather encourages microbial action and formation of soil organic matter (SOM) and soil inorganic carbon (SIC). Dryland soils contain at least as much or more soil inorganic carbon than soil organic carbon (Lal, 2003) – making dryland soils effective carbon sinks.

As valuable as dryland open space carbon sinks are to potential negative climate change mitigation, disturbed soils easily become carbon sources. The formation of calcic horizons can take as long as 10,000 years in aridisols (particularly effective dryland soils for carbon sequestration); calcic horizons in aridisols oxidize quickly when disturbed and credit embodied carbon to the atmosphere. Degradation and desertification are pervasive and results in sizable emission of carbon dioxide into the atmosphere (Lal, 2004). The United States Southwest has a number of deserts where carbon sequestration efficacy could be enhanced through local design interventions. The demonstration project chosen for this study is located in the Sonoran Drylands of the U.S. Southwest at a severely degraded dryland open space along the Lower San Pedro River Basin.

What Is Carbon Sequestration?

Concentration of carbon, nitrogen, and sulfur compounds and other GHGs are increasing as a result of human activities. The negative impacts carbon overburden and associated acute climate change (ACC) have generated a lot of interest for removing carbon from the atmosphere – a process called carbon sequestration. Due to varied studies and goals regarding research into biogeochemical carbon cycles the term “carbon sequestration” has many definitions. Carbon sequestration is, generically, “chemical reactions that remove local sources of carbon dioxide from the atmosphere” (Schlesinger, 1997, p. 3). The Intergovernmental Panel on Climate Change (IPCC) – the international governing body responsible for the Kyoto, Copenhagen, and Cancun Protocols – describes carbon sequestration as the “uptake of carbon containing substances, in particular carbon dioxide, into long-lived reservoirs” (IPCC, 2007). In the context of carbon embodied in natural open spaces, carbon sequestration is defined as the “uptake of atmospheric carbon dioxide during photosynthesis and the subsequent transfer of some fixed C into vegetation, detritus, and soil pools for secure storage” (Lorenz and Lal, 2010, p. 11). This last definition is most useful for designers since vegetation types, maintenance practices (to promote litterfall), and reducing limits of disturbance are all items that can be promoted in design processes.

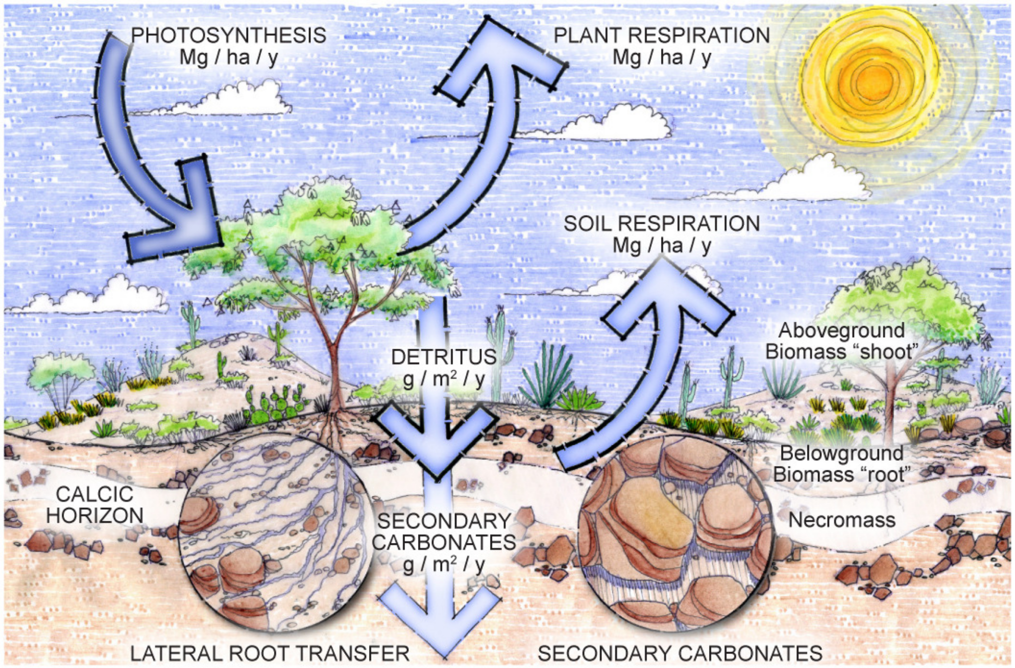


Figure 7. Carbon sequestration process showing general rates of carbon influx and efflux in an aridisol.

Carbon is exchanged between biotic C-pools and atmospheric C-pools through the chemical process photosynthesis. "Photosynthesis is the biogeochemical process that acts to transfer carbon from its oxidized form, carbon dioxide, in the atmosphere to the reduced (organic) forms that result in plant growth" (Schlesinger, 1997, p. 127). During photosynthesis, atmospheric carbon dioxide and water, using light energy, is converted into glucose (carbon fixation):

$$6CO_2 + 6H_2O + \text{photons} \rightarrow 6O_2 + C_6H_{12}O_6$$

Carbon dioxide + water + light energy → oxygen + glucose

"Plant tissue typically contains 45-50% carbon, so division by two is a convenient way to convert units of organic matter to carbon fixation" (Schlesinger, 1997 p. 135; Riechle *et al.,* 1973). A common misconception by designers is that gross primary production (GPP) – the total biomass fixed by vegetation -- is directly equivalent to carbon sequestration. GPP does not account for carbon efflux (loss) through plant and root respiration where carbon is returned through oxidation, as carbon dioxide, to the atmosphere. Plant respiration occurs in both "shoot" and "root" when glucose formed during photosynthesis is oxidized (energy is released) at a cellular level resulting in the building of plant tissue.

While plant photosynthesis and carbon fixation dominates during the day the reverse is true at night when nearly all carbon fixation is lost through plant respiration (Schlesinger, 1997). Carbon flux in the biotic C-pool is also seasonal. During the summer, total photosynthesis in the northern hemisphere exceeds carbon losses due to respiration (Schlesinger, 1997). Thus, temporary sequestration of carbon in plant tissues occurs during the summer when carbon is debited from the atmospheric C-pool. During the winter, carbon embodied in plant tissues is credited to the atmospheric C-pool due to higher levels of decomposition when plants are dormant or leafless (Schlesinger, 1997).

Net primary production (NPP) is equal to GPP minus plant and root respiration. "Differences in soil water use efficiency strong impacts biomass production and levels of soil inorganic carbon" (Lal, 2007, p. 529). "A fraction of NPP is lost to herbivores and in the death and loss of plant tissues, known collectively as litterfall" (Schlesinger, 1997, p. 135). Litterfall and resulting accumulation of soil organic carbon (SOM) in underground biomass, called the true increment by foresters (Schlesinger, 1997). "Plant communities achieve a steady state in living biomass when allocation of woody tissue is balanced by death and loss of older parts" (Schlesinger, 1997, p. 150). The true increment of NPP declines sharply as biomass increases until equilibrium is reached. In the context of carbon sequestration, this means that new open spaces act as carbon sinks until plant communities mature (after approximately 40 years) (Schlesinger, 1997).

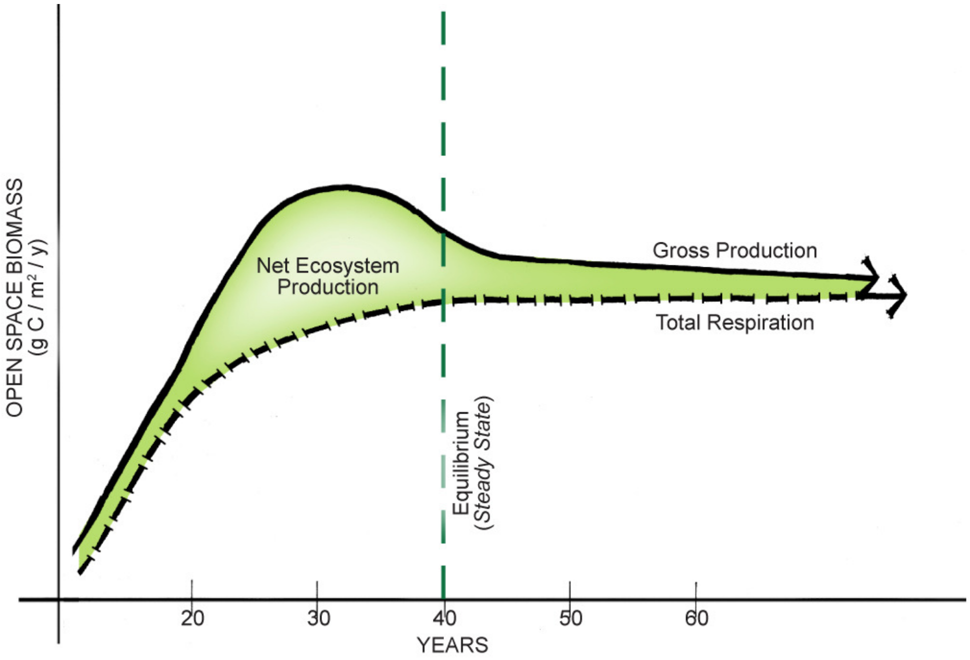


Figure 8. Net Ecosystem Production of Carbon; general trends in gross primary production and respiration during ecosystems development (adapted from Schlesinger, 1997, p. 151)

Mature biomasses are ultimately carbon sources during extended droughts or disturbance events (natural disaster, fire, and human land-use impacts). In the context of disturbance events (such as fire, deforestation, mining, desertification industrial agricultural practices, etc.), carbon sequestration in aboveground biomass ("shoot") is temporary. In dryland systems desertification results in degradation of NPP and decline in efficacy of carbon sequestration processes and benefits. Natural fire events result in a total loss of NPP and any carbon sequestration benefits; negative human land-use impacts "increase the frequency and area of fire" (Schlesinger, 1997, p. 151). Biomass in underground biomass ("root") is naturally insulated against natural fire events (though artificial fire suppression can result in extremely hot fires that destroy underground biomass).

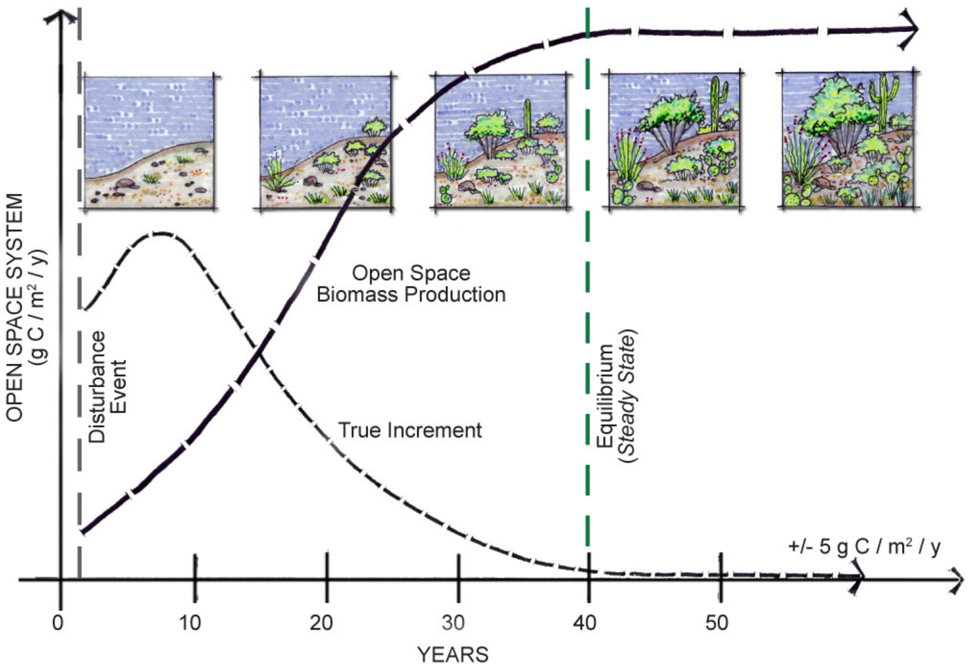


Figure 9. Open space biomass production; general trends in biomass production and true increment.

Due to potential loss of biomass (and all associated carbon sequestration benefits) due to deforestation, landscape degradation, and other negative human impacts, carbon embodied in soil has longer residence times than aboveground biomass. Carbon is accumulated in soils through litterfall and later root transfer (Schlesinger, 1997). “The annual accumulation of organic matter per unit of land is a measure of NPP, often expressed in units of g C / m^2 / y” (Schlesinger, 1997, p. 135) as opposed to carbon influx expressed in units of Mg C / ha / y. Lateral root transfer of carbon and leaching in soils as a result of chemical reactions, catalyzed by water, results in the formation of pedogenic (or secondary) carbonates.

$$2CO_2 + 2H_20 \rightarrow 2H^+ + 2HCO_3^-$$

Carbon dioxide + water → hydrogen + bicarbonate

Sources of carbon utilized for the formation of secondary carbonate are typically from microbial action in soils and lateral carbon transfer from root respiration. Secondary carbonates naturally form in biomasses in a steady state with chemical reactions between carbon released during root respiration and soil-borne calcium, magnesium, and iron. This process is very slow, especially in drylands, where “soil development occurs slowly due to limited weathering and leaching of the soil profile” (Schlesinger, 1997, p. 115). Dryland ecosystems often develop calcic horizons that form over long periods of time; often exceeding 10,000 years:

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + H_20 + CO_2^-$$

Calcium + bicarbonates → calcium carbonate + water + carbon dioxide

In most calcic horizons, “calcium carbonate has accumulated at rates of 1.0 – 5.0 g C / m^2 / y from the downward transport of Ca-rich minerals deposited from the atmosphere” as alluvial clays, and airborne iron oxide (Schlesinger, 1997, p. 115). Secondary carbonates and other SIC are extremely stable and require high temperatures to release carbon -- as in fossil fuel combustion. The rate of SIC sequestration is low at 0.03-0.05 Mg C / ha / y (Lal, 2004; Schlesinger, 1997). “Turnover time of C in secondary carbonates may be 30,000 to 90,000 years” (Lal, 2004, p. 536). Release of SIC through oxidation as carbon dioxide is increasing due to fossil fuel combustion and now “exceeds the rate at which other components of the Earth’s biogeochemical system can take up carbon so as to moderate or buffer changes to the atmosphere“ (Schlesinger, 1997, p. 7). Interest in reducing carbon in the atmospheric C-pool has resulted in rising interest in enhancing and preserving existing natural carbon sinks. Land management and design interventions can encourage longer residence times of carbon in open space systems.

Chapter 4

RESEARCH DESIGN AND INTERVENTIONS

Efficacy of carbon dioxide debits from the atmospheric C-pool through photosynthesis and the subsequent transfer of C to vegetative biomass, to soil organic carbon, and ultimately to a stable inorganic state over time can be enhanced through design. Carbon sequestration in open spaces for agricultural production can be modified to increase carbon sequestration efficacy through modified land management. Dryland open space systems in particular can be enhanced through design manipulation of water, establishment of natural vegetative biomass, preservation / enhancement of key aridic soils, modified agricultural practices to develop agricultural soils as carbon sinks, and the offsetting of carbon emissions through the use of locally grown biomass for energy production. Benefits derived from carbon sequestration, while minor on a small scale are increased significantly when applied to regional-scale open spaces. Transfer of carbon from the atmospheric C-pool can be enhanced in dryland open space systems (particularly in disturbed or degraded landscapes) through enhancement, preservation, and restoration of key system components: water, vegetation, and soils.

The presence of water directly impacts rates of carbon transfer and carbon sequestration. Water is essential to the biogeochemical processes of photosynthesis, formation of biomass, lateral carbon transfer from biomass to soils, and formation of calcic / magnesium horizons through leaching. Carbon transfer from soils to large water bodies through erosion and deposition ultimately form the large carbon “sinks”; the largest of these being the oceanic C-pool where carbon is subjected to low temperatures and high pressures. In dryland open spaces, where water is especially scarce, carbon sequestration efficacy is greatest where water is concentrated: riparian corridors and wetlands. Restoration and preservation of dryland riparian and wetland vegetative systems would greatly increase benefits of carbon sequestration.

Vegetative biomass is critical to open space carbon sequestration efficacy. Organisms regulate the flux of carbon between atmosphere and the biosphere through primary production and decomposition (hence “bio” in biogeochemical cycles) (Schlesinger, 1997). During succession and prior to reaching a steady state (open space maturity / equilibrium occurs in roughly 40 years) carbon sequestered in aboveground vegetative biomass exceeds carbon plant and root respiration efflux. Once equilibrium has been achieved in dryland open spaces efflux of carbon through lateral root transfer establishes longer-term residence times of carbon in soils and the building of calcic horizons. Revolving establishment of natural open spaces (every 40 years) could potentially offset significant amounts of carbon emissions. With combustion of fossil fuels releasing an estimated 7 Pg C into the atmosphere each year (Salati *et al.,* 2010), atmospheric C-pool credits due to emissions must be drastically reduced for the benefits of open space carbon sinks to be seen.

Soils are also key components of successful open space carbon sequestration. Carbon transfer from above-and-belowground biomass through lateral root transfer, litterfall, bioturbation, and microbial action coupled with leaching in deep soils forms long-term C-pools. Organic carbon readily bonds with calcium, magnesium, iron, and other elements found in soils. In dryland soils (particularly aridisols) carbon bonds with calcium to form stable secondary carbonates (calcium carbonate) which form calcic horizons through leaching (Lal

2007). Carbon embodied in aboveground biomass can be lost through natural means (primarily forest fires) and human impacts (direct harvesting, grazing impacts, increased frequency of forest fires, and other land-uses that degrade the efficacy of open spaces biogeochemical processes). Carbon in soils has long residence time and is more resilient to impacts than aboveground biomass. Carbon sequestered in soils in a stable state (secondary carbonates) do nt quickly oxidize when exposed to the atmosphere. However, disturbed soils are subjected to increased microbial action and, with the presence of water, the pedogenic C-pool can be severely impacted; reducing impacts to soils protects an important carbon sink. "Total annual emission of C due to erosion-induced land degradation in dryland ecosystems may be 0.23-0.29 Pg C / y " (Lal, 2003 p. 530).

Carbon sequestration efficacy is enhanced in dryland open spaces where water is readily available, there is significant natural biomass, and aridisol soils are well drained and calcium-rich (as evidenced by an established calcic horizon). Conversely, efficacy of carbon sequestration is lessened significantly in degraded dryland open spaces. For example, impacts resulting in increased desertification – defined "as the irreversible loss of production and ecological functions indicated by soil erosion, loss of biodiversity, and lower productivity" (Arnalds, 2000, p. 153) severely reduce carbon sequestration efficacy. Land degradation in drylands result from climatic variations and human impacts (Lal, 2003). Increased runoff, loss of biodiversity, and soil erosion further impair carbon sequestration efficacy. Degraded open spaces release carbon through decomposition and oxidation, which is quickly and credited to the atmospheric C-pool. Open space carbon "sinks" can easily become carbon sources in conjunction with negative human land-use. Reducing human land-use impacts to existing natural open space – the most efficient open space carbon sinks – reduces carbon credits to the atmospheric C-pool.

Carbon Typologies

Carbon sequestration key system components (water, vegetation, and soil) can be manipulated through modified land-use design and management to encourage, enhance, and preserve natural open space carbon sinks. Open space carbon is estimated by calculating the amount of carbon sequestration (estimated in Mg C / ha / y) in dryland open space C-pools. "Commonly observed rates of C sequestration in soil and biomass range from 0.04 to 0.40 Mg C / ha / year for soil organic carbon and 2-4 Mg / ha / y for biomass" (Lal, 2004, p. 537). For the purposes of this study, open space carbon sequestration is calculated by estimating both soil organic carbon and biomass.

In dryland open space systems observed rates of carbon sequestration in aboveground biomass tend to be lower due to low water availability. Observed rates of long-term transfer of carbon from aboveground biomass to steady state soil inorganic carbon tend to be higher due to the common formation of secondary carbonates – typically through the reactions of soil inorganic carbon with calcium and result in deep calcic horizons. Observed rates of carbon sequestration in desert vegetation vary significantly from 2 Mg C / ha / y in areas with average coverage of Mesquite (*Prosopis spp.)* and Thorntrees *Acacia spp.)* to 0.002-0.004 Mg C / ha / y in dryland scrub areas (Lal, 2004, Glenn, *et al.,* 1993). A specific measurement of individual dryland open spaces significantly increases the accuracy of quantifying carbon sequestration. Designers often do not have time, expertise, or resources to tailor calculations nor do they need specific measurements to determine impacts of design interventions. General ranges of dryland open space carbon sequestration can be summarized in five open space typologies: hydric, mesic, aridic, biomass for energy agriculture, and traditional agriculture.

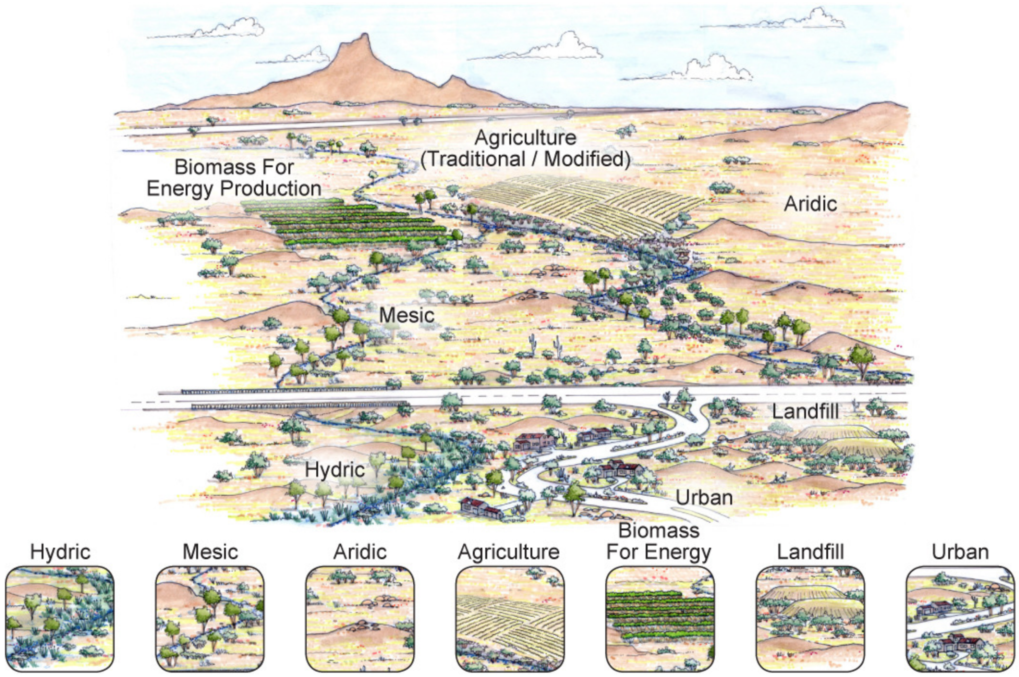


Figure 10. Carbon Typologies: hydric, mesic, biomass for energy production, and traditional / modified agriculture

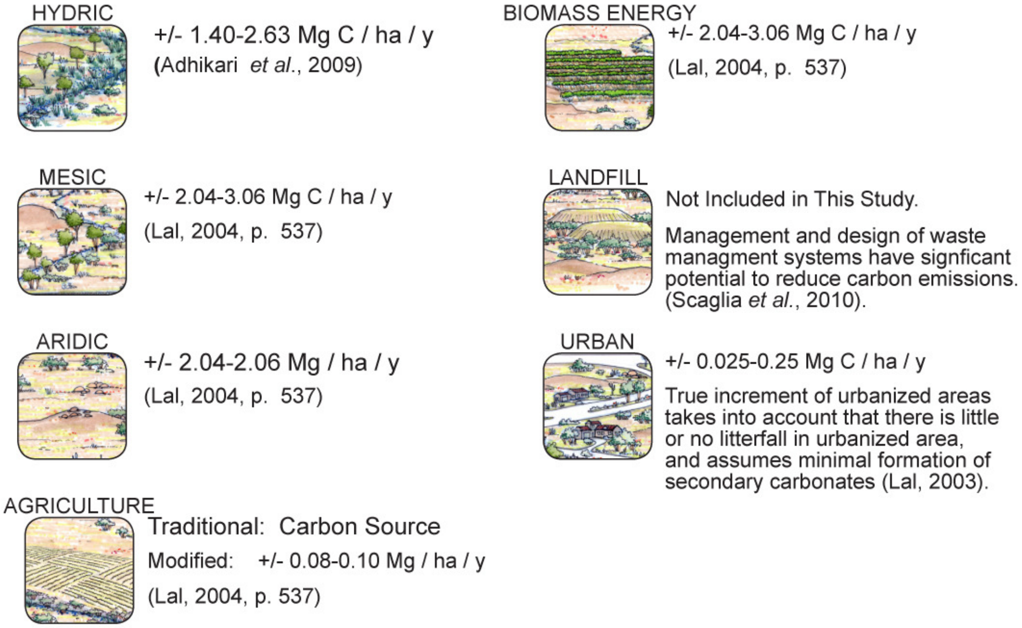
Hydric (wetland) vegetative systems receive a significant amount of moisture, an established vegetative biomass, and soils that are rich in organic and inorganic carbon (particularly calcium carbonate) (Adhikari *et al.,* 2009). Horizontal transfer of carbon embodied in litterfall and lateral exchanges of carbon from root respiration settles in wetland soils making hydric systems profoundly efficient carbon sequestration systems. Some dryland wetland systems have become ephemeral (and thus are not as efficient at carbon sequestration as temperate wetlands). These ephemeral wetlands may actually release carbon if water level is too low or human impacts result in oxidation of soils (Adhikari *et al.,* 2009). Dryland wetlands still release dissolved carbon into adjacent open space systems and capture carbon rich sediments. Carbon sequestration efficacy in wetland vegetative systems varies widely depending on vegetative conditions with dryland systems sequestering less carbon than wetter biomass. Typical range of carbon sequestration is 1.40-2.63 Mg C / ha / y (Adhikari *et al.,* 2009). Dryland wetland open space carbon sequestration efficacy tends to be at the low end of this range but dryland wetlands adjacent to natural riparian systems can be effective as wetter, temperate wetlands. It is assumed in this study that high range carbon sequestration observations could be seen in perennial designed / restored wetlands.

Mesic (riparian) vegetative systems receive a moderate amount of moisture, a vegetative biomass that is inundated with water and at other times dry, and sediment-rich soils. It is important to note in this study that the riparian typology does not include the channel itself, which routinely looses newly established biomass during yearly rain events. Erosion of the more permanent riparian corridor (and subsequent loss of biomass) is taken into account in this study. Furthermore, an existing biomass within this typology typically consists large hardwood species: Mesquite (*Prosopis spp.)*, Thorntrees (*Acacia spp.)*, Ironwoods (*Olneya tesota)* Arizona Sycamore (*Platanus wrightii*) and Cottonwoods (*Populus spp.*). Mesic open space systems have been observed to sequester 2.04-3.06 Mg C / ha / y in erosion control areas of restored riparian systems (Lal, 2004, p. 537). While sequestration efficacy may actually be higher in undisturbed dryland riparian systems, flashfloods and desertification may result in lower actual sequestration efficacy (or a total loss). Restoration of degraded riparian soils can significantly improve the carbon pool in terrestrial drylands as the majority of carbon lost to mesic systems is through erosion (Lal, 2003). For the purposes of this study it is assumed that native water flow in a riparian channel is maintained.

Aridic (dry) vegetative systems receive low amounts of moisture, have long-established but dryland-acclimated vegetation, and typically aridic soils with deep calcic horizons. Carbon sequestered in dryland terrestrial ecosystems (including mesiscapes, xeriscapes, and even degraded desert remnants) has a long residence time and is not remitted to the atmospheric C-pool (Lal, 2003). While biomass is relatively low due to low amounts of moisture a year-round growing season and microbial action coupled with calcium-rich aridic soils catalyze transfer of carbon from aboveground biomass to belowground, stable carbon pools. There is tremendous range in carbon sequestration efficacy for dryland vegetation. This study assumes that aridic systems are situated on aridic soils, are desert scrub or other low biomass ecosystem with observed range of carbon sequestration of 2.04-2.06 Mg / ha / y (Lal, 2004, p. 537).

Traditional agriculture carbon pools are heavily degraded during planting and harvest – observed carbon sequestered in soils are reduced with each harvest in a typical crop rotation. However, modifications in agricultural practices increase can in create carbon sinks (instead of sources) with enhanced carbon sequestration rates observed between 0.08 and 0.10 Mg / ha / y (Lal, 2004, p. 537). Modified agriculture practices – such as longer growing cycles, smaller plantation-style farming, growing native plant species, greater biodiversity, and use of carbon additives as fertilizer – can increase carbon sequestration efficacy significantly. Traditional agricultural systems are never in equilibrium and thus, carbon "injections" (carbon fly ash and biochar) in agricultural soils improves soil quality and production over time while establishing farmland soils as a potentially large carbon sink (Lal, 2003). Studies of biochar additions showed productivity in agricultural lands could be increased 20-220% with an application of 0.4-8.0 Mg C / ha / y (Lehmann and Rondon, 2006). While the biotic C-pool may be enhanced with the addition of available soil nutrients, increased growth of biota is temporary. Short-term increases in growth associated with carbon uptake are ultimately offset by the decreasing availability of other available nutrients – particularly soil minerals become a limiting factor to biota growth. Soil minerals, typically formed through weathering of mineral deposits, can take long periods of time to be deposited. Additional research is ongoing as to the benefits of modifying agricultural soil management. With a total carbon sequestration potential of 185 to 514 million Mg of C / hectare / year in U.S. croplands alone even the low-end observations of agricultural soils as carbon sinks show great potential (approximately 1,000 to 28,000 million Mg C / ha / y) (Lal, 2004; IBI, 2009). It is important to note that carbon in soils, as in aboveground biomass, reaches a steady state after approximately 40 years after which additional carbon additives are quickly oxidized (Schlesinger, 1997). For the purposes of this study a low estimate for modified agricultural practices is assumed. Biomass for energy production (perennial biomass) also has potential to act as a vegetative carbon sink as well as reducing demand for fossil fuels. Biofuel production for direct combustion has a carbon sequestration rate of 2-3 Mg / ha / y (Lal, 2004, p. 537). This sequestration rate accounts for carbon sequestered in aggressive native, renewable cover crops, and does not take into account factors such as fossil fuel offsets or reducing efficacy due to constraints (such as storage, transport, and production processes).

Potential urban growth / rehabilitation of existing privately-owned properties in Mammoth provide an opportunity for developing a truly regenerative built environment. However, the complexities of designing such a system coupled with associated investments are not anticipated. In this study, the existing and proposed urban environments are assumed to offer low carbon sequestration efficacy roughly 0.025 and 0.25 Mg C / ha / y with minimal overall sequestration enhancement (or loss) for the demonstration project. Additional research is necessary to determine the true increment of urbanized areas. This proposed number for the true increment of urbanized areas takes into account that there is little or no litterfall in urbanized area, and assumes minimal formation of secondary carbonates (Lal, 2003).


HYDRIC
+/- 1.40-2.63 Mg C / ha / y
(Adhikari *et al*., 2009)

MESIC
+/- 2.04-3.06 Mg C / ha / y
(Lal, 2004, p. 537)

ARIDIC
+/- 2.04-2.06 Mg / ha / y
(Lal, 2004, p. 537)

AGRICULTURE
Traditional: Carbon Source
Modified: +/- 0.08-0.10 Mg / ha / y
(Lal, 2004, p. 537)

BIOMASS ENERGY
+/- 2.04-3.06 Mg C / ha / y
(Lal, 2004, p. 537)

LANDFILL
Not Included in This Study.
Management and design of waste managment systems have signficant potential to reduce carbon emissions. (Scaglia *et al*., 2010).

URBAN
+/- 0.025-0.25 Mg C / ha / y
True increment of urbanized areas takes into account that there is little or no litterfall in urbanized area, and assumes minimal formation of secondary carbonates (Lal, 2003).

Figure 11. Summary of carbon typologies and sources.

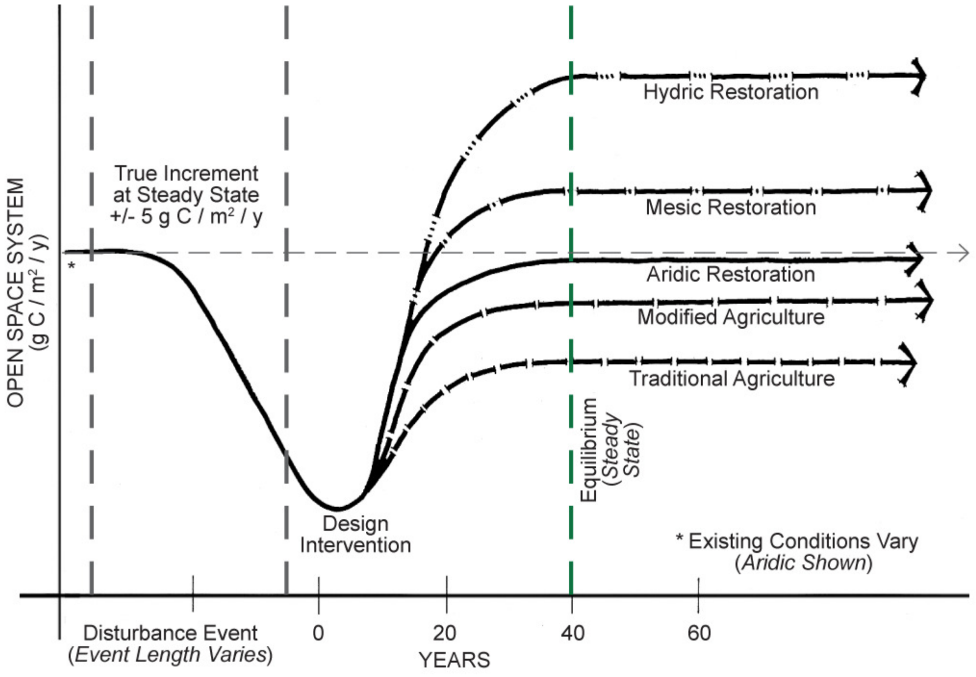


Figure 12. General trends in biomass production and true increment of design typologies after open space disturbance.

Impacts of design interventions to the carbon capacity of dryland open space systems are calculated by estimating carbon exchange in existing open space (base case) compared to projections of carbon sequestered in a modified system (design intervention). General trends in observed carbon sequestration can only give a general picture of the true increment and efficacy. At a regional scale, however, general observations can help designers predict design impacts and determine natural open space carbon sequestration benefits. It is important to note that while carbon is semi-stable aboveground biomass in the built environment, very little carbon is transferred to belowground C-pools (and a more stable state) by local litterfall (Lal, 2003). Generally, natural dryland open spaces are more effective carbon sequestration systems (particularly regional-scale open spaces).

Demonstration Project

A successful demonstration project highlighting carbon sequestration efficacy in dryland systems should include the full range of carbon typologies (described above): hydric, mesic, aridic, biomass for energy production, and traditional agriculture. “The U.S. Department of Energy (DOE’s) National Energy Technology Labs (NETL) is engaged in a research and development carbon sequestration program focusing on carbon capture and sequestration (CCS) technologies with significant potential for reducing GHG emissions and controlling global climate change” (NETL, 2007, p. 61). The NETL has identified potential reservoirs for terrestrial carbon dioxide in addition to their value as recreational lands. In the drylands of the United States Southwest, the NETL determined that carbon sequestration efficacy would be greatly increased by “enhancing existing plant growth and reintroducing woody plant species along riparian areas and reestablishing native grasses and shrubs in upland areas” (NETL, 2007, p. 61). The limiting factors for carbon sequestration efficacy in identified dryland open spaces would be: availability of water, establishment of native vegetation, and soil quality.

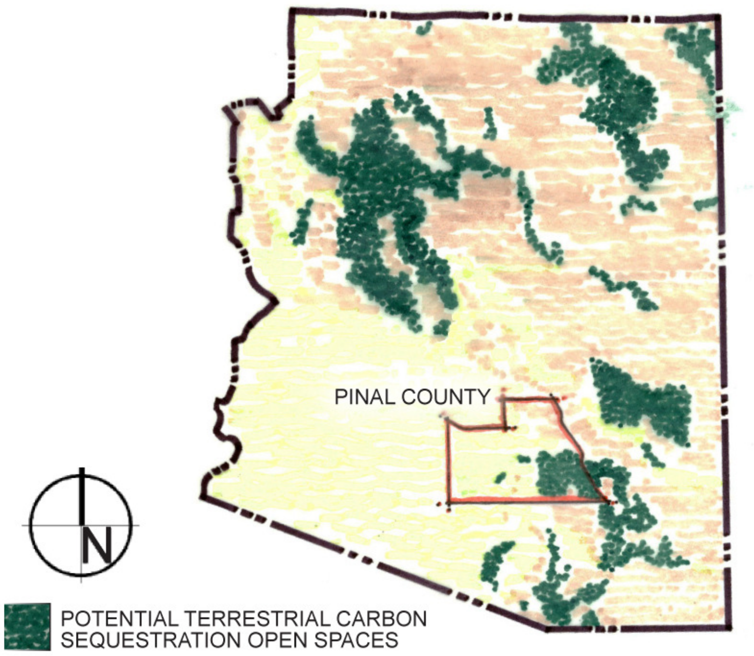


Figure 13. Potential carbon sequestration areas in Arizona (adapted from NETL, 2010).

One potential terrestrial carbon sequestration opportunity identified by the NETL was the Lower San Pedro River Basin in Pinal County, Arizona (NETL, 2007). As a demonstration site for estimating and analyzing carbon sequestration efficacy the Lower San Pedro is ideal with natural access to water, successfully established native vegetation, and aridic soils with deep calcic horizons (Natural Resources Conservation Service, 2011; Brown and Lowe, 1978). The San Pedro River is one of the last undammed rivers in the American Southwest; it is of major ecological importance as it hosts two-thirds of the avian diversity in the United States (Natural Resources Conservation Service, 2011).

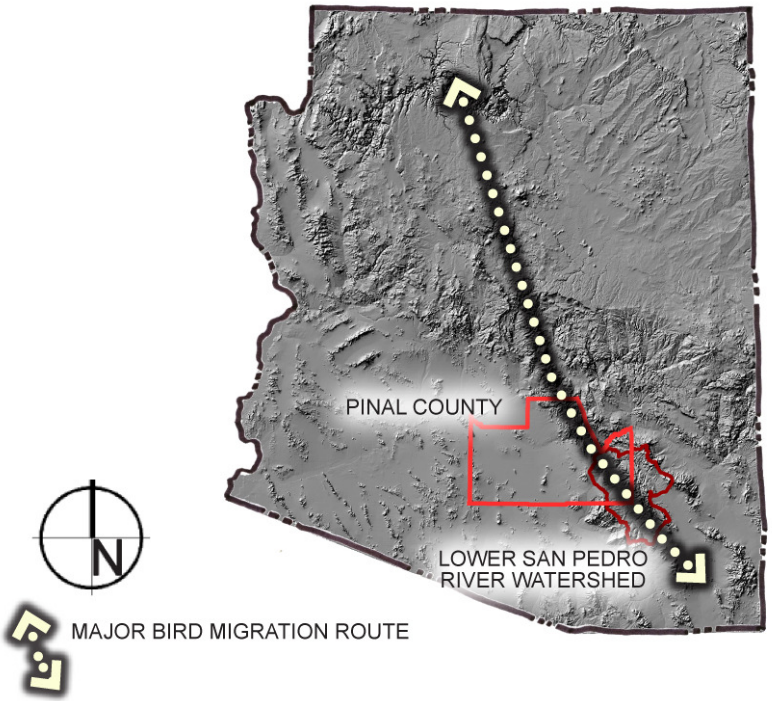


Figure 14. Important bird migration routes through Arizona (Natural Resources Conservation Service, 2011).

Native vegetation along the Lower San Pedro includes Lower and Upland Sonoran Desert Scrub, which receives considerable rainfall in the winter as well as during the summer resulting in densely vegetated and diverse landscape (Brown and Lowe, 1978). "The Sonoran desert is characterized by truly large cacti - notably Saguaro (*Carnegiea gigantiea*). In addition, other cacti include Teddy-Bear Cholla (*Cylindropuntia bigelovii*), Chain Fruit Cholla (*Opuntia fulgida*), organ pipe cactus (*Stenocereus thurberi*), and barrel cactus (*Echinocactus spp.* and *Ferocactus spp.*). Mesquite (*Prosopis)*, Desert Ironwood (*Olneya tesota*), and Palo Verde (*Parkinsonia spp.*) are also common" (Brown and Lowe, 1978).

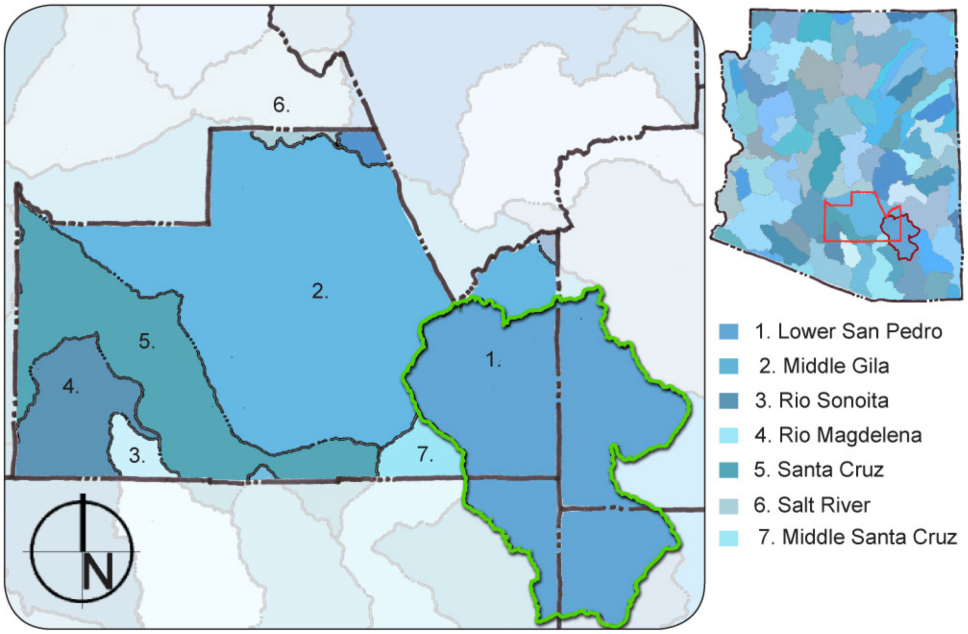


Figure 15. Hydrologic Unit Code Areas: Drainage Basins of the Lower San Pedro Watershed (Arizona Land Resources Information Service, 2011).

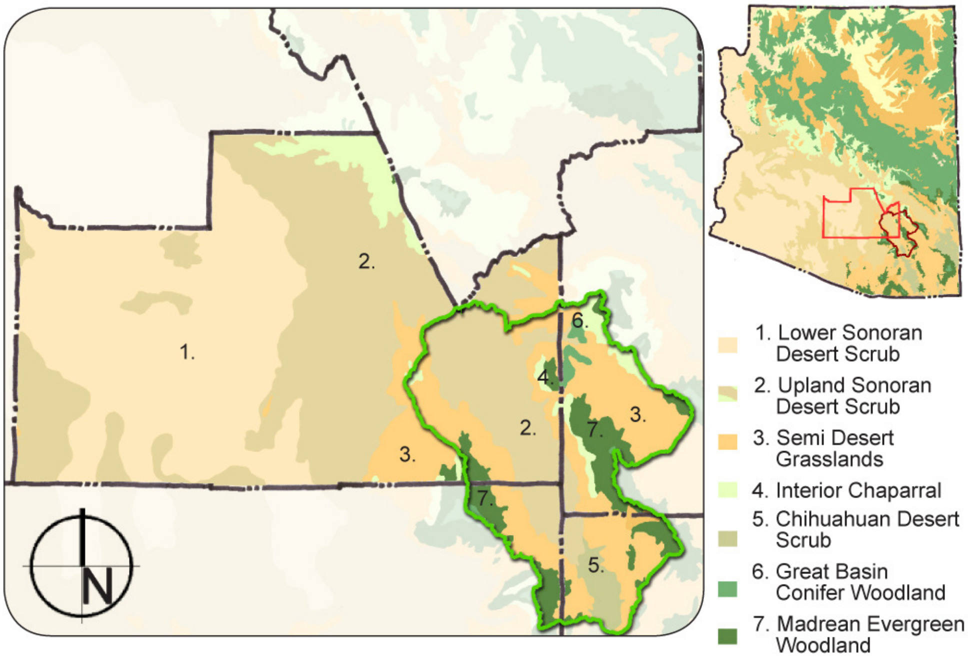


Figure 16. Biotic Communities of the Lower San Pedro Watershed (Brown and Lowe, 1978; Arizona Land Resources Information Service, 2011).

There are several aridic soils present in the Lower San Pedro Basin. Hathaway soils are Aridic Calciustolls – calcium-rich, loamy, deep, and well-drained soils with low available water capacity and moderately rapid permeability (Natural Resources Conservation Service, 2011). Available water (both riparian and wetland vegetative systems), high vegetative biomass with high biodiversity, and aridic soils coupled with being of major ecological importance as a bird migration route make the Lower San Pedro River Basin an ideal location for a dryland carbon sequestration enhancement / conservation demonstration project.

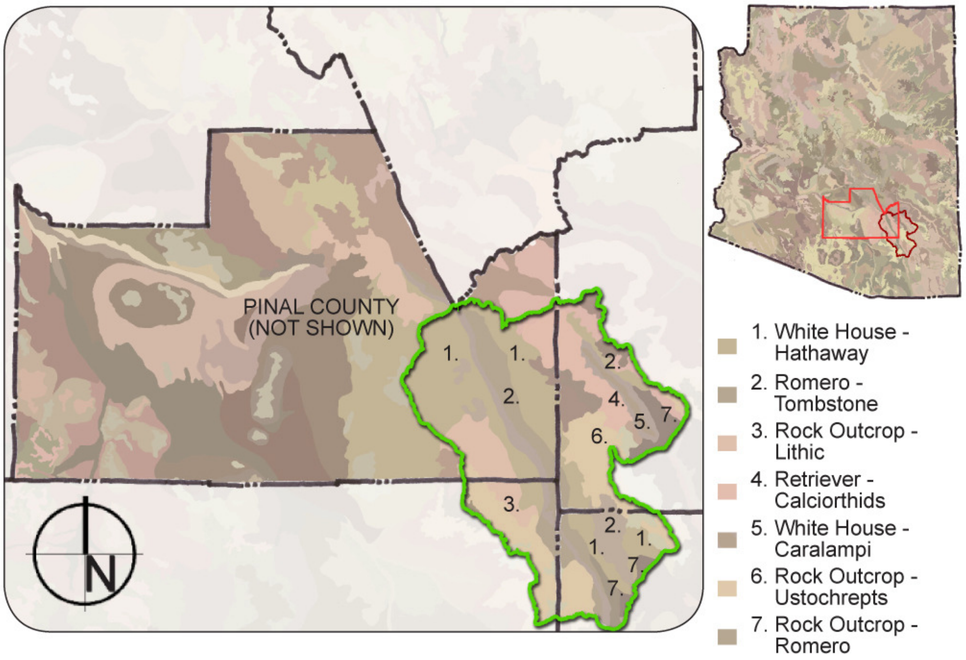


Figure 17. Soil Inventory of the Lower San Pedro Watershed (Natural Resources Conservation Service, 2011; Arizona Land Resources Information Service, 2011).).

A demonstration project enhancing the benefits of dryland carbon sequestration -- or “carbon park” – also improves the quality of life for local communities by providing ecological, social, and economic benefits. The Lower San Pedro River Basin has several communities that would greatly benefit from open space improvements that generate local interest as an ecotourism destination, provides valuable natural open space amenities, habitat for local flora and fauna, and opportunities for improved agriculture which responds to a growing demand for more sustainable farming practices (described below). The relationship between local communities and the carbon park is reciprocal; local open space improvement projects directly benefit from local volunteerism and community vestment. Furthermore, for an open space system to achieve prime carbon sequestration efficacy human land-use impacts must be mitigated.

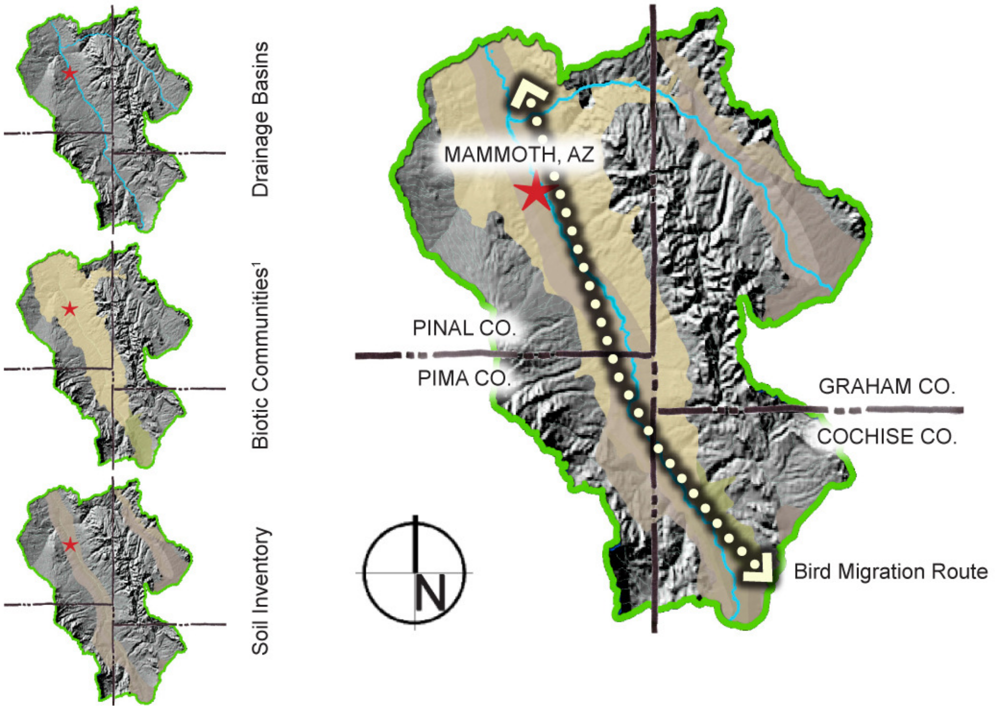


Figure 18. Composite map of drainage basins, biotic communities, and soil inventory for the Lower San Pedro River Watershed (Natural Resources Conservation Service, 2011; Arizona Land Resources Information Service, 2011; Brown and Lowe, 1978).

Existing Conditions

The Town of Mammoth, Arizona is – a declining mining town – is an ideal location for a carbon park. Mammoth is located just south of the confluence of the Lower San Pedro River and Aravaipa Creek (both important habitat corridors for migrating birds) (Natural Resources Conservation Service, 2011). Mammoth is also located in the edge of the Sun Corridor – a region between Phoenix and Tucson of planned development as a significant future "megapolitan" region. The doubling the current population of 5 million and build-out to rival the City of Chicago, Illinois in size is anticipated (The Morrison Institute, 2008). Such aggressive growth of the built environment (exacerbated by the pace of demand-development) substantially increases the risk of negative human impacts to remnant open spaces (particularly lowered water quality, loss or degradation of critical habitat, and disturbance of soil C-pools). Community vestment and conservancy efforts geared toward protecting the natural assets of the Lower San Pedro River Basin are imperative.

Mammoth and nearby San Manuel Mines were the founding *raison d'etre* for the Mammoth community until they closed in 2006. The Town of Mammoth municipal limits cover a significant portion of the region to include the entirety of the Mammoth Mine located west of Mammoth proper. Prior to 2006 the local community and employment opportunities were focused on the two adjacent mines. Local economic opportunities were drastically reduced with the shutting of the primary employment at the mines; much of Mammoth and neighboring San Manuel have been allowed to fall into disrepair. All remaining mining buildings have been demolished and remediation efforts include capping mine tailings and reworking disturbed drylands. The only visible remnants of mining operations have been concentrated in Ore Cart Trail Park, an impressive wooden trellis used to transport copper ore to smelting plants, a series of capped tailings earthworks, and the massive artificial Mammoth Mine Peak itself at the old Mammoth Mine.

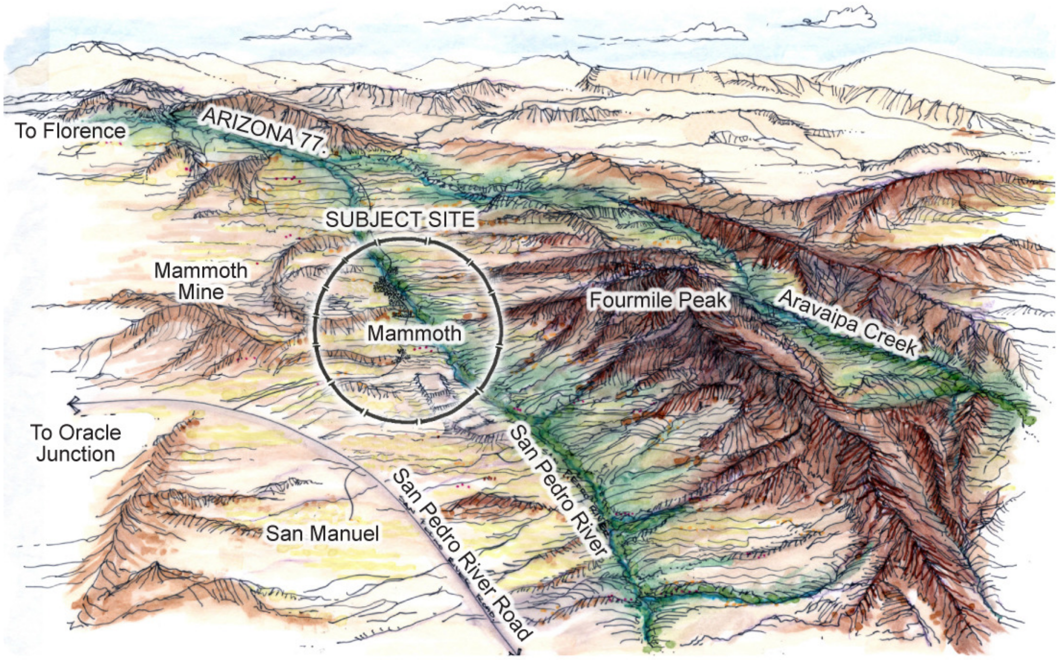


Figure 19. Illustrative perspective of the Lower San Pedro River.

To the east of Mammoth, the Lower San Pedro River plies its northward course. "The San Pedro River begins in the mountains near Cananea, Sonora, Mexico and flows north more than 150 miles through the southeast corner of Arizona to join the Gila River near Winkelman, Arizona" (Arizona Department of Environmental Quality, 2010). The San Pedro is fed during storm events (mainly in the winter and summer) by numerous desert washes – the two largest are the Tucson Wash (north of town) and Mammoth Wash (south of town). The water coursing through the Lower San Pedro was once perennial but due to human water use the river is now ephemeral.

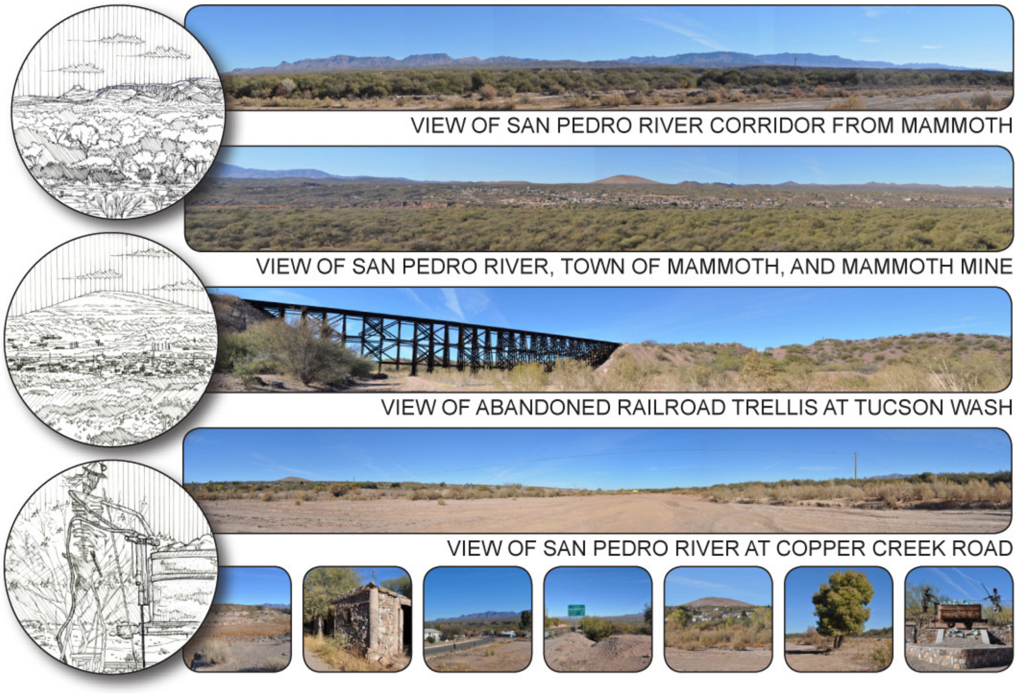


Figure 20. Site Photography and Sketches of Mammoth Arizona showing biomass, existing riparian corridor, and sculpture at Ore Cart Trail Park.

The majority of native biomass -- Lower and Upland Sonoran Desert Scrub -- is concentrated along aridic soils in well-drained areas and along the flood plain of the San Pedro River and the two major washes. Enhancing existing plant growth and reintroducing woody plant species in wetlands, riparian, and upland systems, developing agricultural soil sinks, and establishing biomass for energy requires reliable sources of water (NETL, 2007). It is important to note that a project demonstrating the benefits of enhancing carbon sequestration efficacy in soils and vegetation in dryland open spaces is limited by availability of surface water.

In the context of the Mammoth demonstration project site the surface waters pf the San Pedro are highly regulated by the Arizona Department of Water Resources (ADWR) which defines surface waters as “water of all sources, flowing in streams, canyons, ravines or other natural channels, or in definite underground channels, whether perennial or intermittent, floodwaters, wastewaters, or surplus water, and of lakes, ponds and springs on the surface” (Arizona Revised Statute, 2011, Title 45, § 101). Due to the value of water in Arizona drylands, the Arizona Department of Water Resources (ADWR) requires permits in order to divert surface water. Water permits are approved by the tenet “first in time, first in right” for beneficial water uses (Arizona Revised Statute 2011, Title 45, § 141b). Beneficial uses include “domestic, municipal, irrigation, stock watering, water power, recreation, wildlife including fish, nonrecoverable water storage, and mining uses (Arizona Revised Statute 2011, Title 45, §141b).

The Lower San Pedro watershed receives little precipitation, with 10-15 inches of rain and 0-5 inches of snow. Springs historically provided perennial flow to segments of the San Pedro River and other streams within its watershed. “The San Pedro is perennial, flowing continuously throughout the year in many places as the result of groundwater discharge; however increasing population and drought conditions have depleted groundwater resources resulting in lower perennial flow” (Arizona Department of Environmental Quality, 2010). Reduced water available to the San Pedro River surface waters (exacerbated by growing populations in the Tucson Metropolitan area) have resulted in severe disturbance to the river’s natural flow – during especially hot seasons the river no longer flows at all. Over a short period of time the Lower San Pedro has been further impaired by mining pollution (mainly copper and selenium), reduced water flowing in the San Pedro River from groundwater sources, impacted low-flow channels (mainly due to off-road vehicles), erosion, and sedimentation. Invasive plant species such as Buffelgrass (*Pennisetum ciliare*) and Red Brome Grass (*Bromus rubens*) are particularly widespread in disturbed areas.

Opportunities

Enhancing carbon sequestration efficacy in degraded open space is possible through conservation and restoration efforts. "If only 2/3 of C lost to [world-wide] desertification would be sequestered through desertification control, adoption of recommended land-use, and soil management practices, this would amount to 12-20 Pg C over a 50-year period" (Lal, 2003, p. 531). Restoration of the riparian corridor near Mammoth will be a substantial challenge but could result in significant increases in carbon sequestration benefits.

Carbon sequestration benefits achievable in the Mammoth area include "long-term improvements in soil quality, productivity, increased land value, reduction of erosion and sedimentation, improvement in water quality, and decrease in net emission of greenhouse gases into the atmosphere" (Lal, 2003, p. 539). The remnant dryland open spaces around Mammoth's have been significantly degraded or impaired through desertification caused by diversions of water from the San Pedro River but could recovered through policy and design interventions.

Specific challenges to overcome include: restoring severely degraded local washes and impacted the low-flow channel of the San Pedro River due to unregulated off-road vehicles, linking fragmented Upland and Lower Sonoroan

Desert Scrub vegetation at critical intersections of the Lower San Pedro River and Tucson and Mammoth Washes, reestablishing, hydric (wetlands) and mesic (riparian) vegetative systems through the restoration of natural surface water flow, and establishing agricultural systems that provide economic opportunities as well as acting as important carbon sinks.

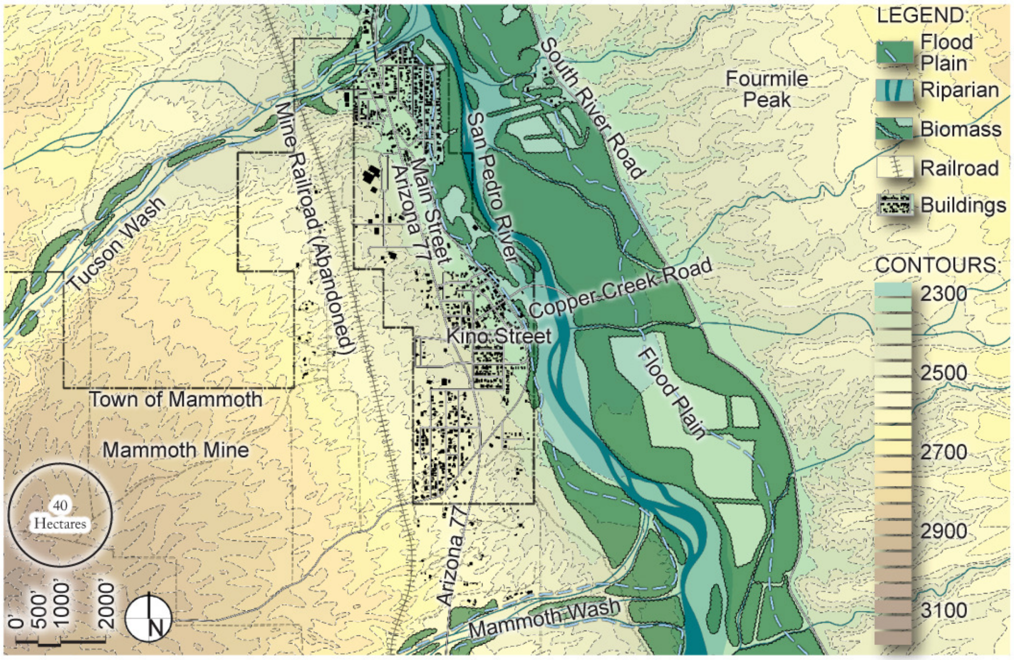


Figure 21. Analysis of existing site conditions of Lower San Pedro River at Mammoth, Arizona.

Water policies will have to be accommodated / modified to allow for a successful carbon sequestration demonstration project; the prototype project included in this study assumes ongoing efforts by conservationists and policy-makers to restore surface water flow to the San Pedro River are accomplished in tandem with the demonstration project. Additionally, rainwater harvesting is not specifically addressed by the by the Arizona Revised Statute (with the exception of systems that divert water flowing in channels – such as diversion dams and macro catchments in washes. Modifications to land forms may be more acceptable water catchments. Landform catchments include tilted plane, rounded, sheet, and micro catchments. The prototype project assumes that rainwater catchment systems (with the exception of diversion systems) would allow for concentration of rainwater for establishing vegetative biomass.

Tilted Plane Catchment Diversion Dam Rounded Plane Catchment

Sheet Catchment Micro Catchment Macro Catchment

Figure 22. Water catchment and concentration systems.

The closing of the San Manuel and Mammoth Mines have had removed the original economic *raison d'etre* for the Town of Mammoth and outlying communities resulting in significant decline (as evidenced by dwindling population, dilapidated infrastructure, abandoned structures, and lack of economic opportunities). However, there is already evidence of a nascent environment-based tourism trade at the nearby Biosphere 2. The Biosphere 2 is a local "research, outreach, and teaching center focused on living systems" currently a department of the University of Arizona College of Science (University of Arizona, 2011). The Town of Mammoth and the Lower San Pedro River Watershed are also centrally located between the pillars of the Sun Corridor -- Phoenix and Tucson, Arizona. Conservation and restoration efforts coupled with ecological tourism (eco-value) could be an important economic driver for the Mammoth area especially as the Sun Corridor becomes increasingly urbanized.

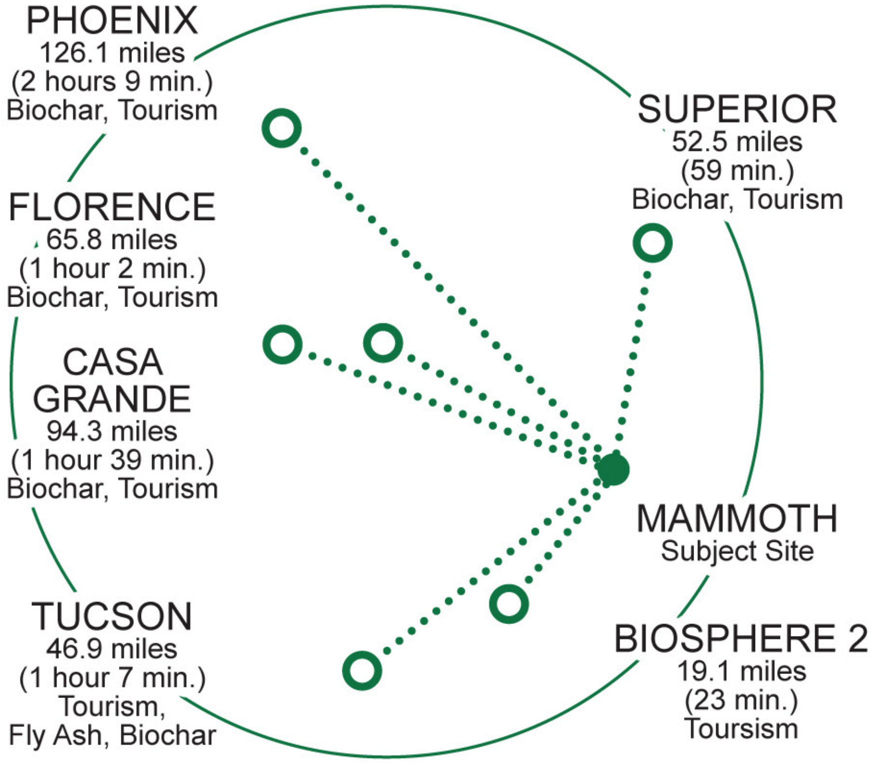
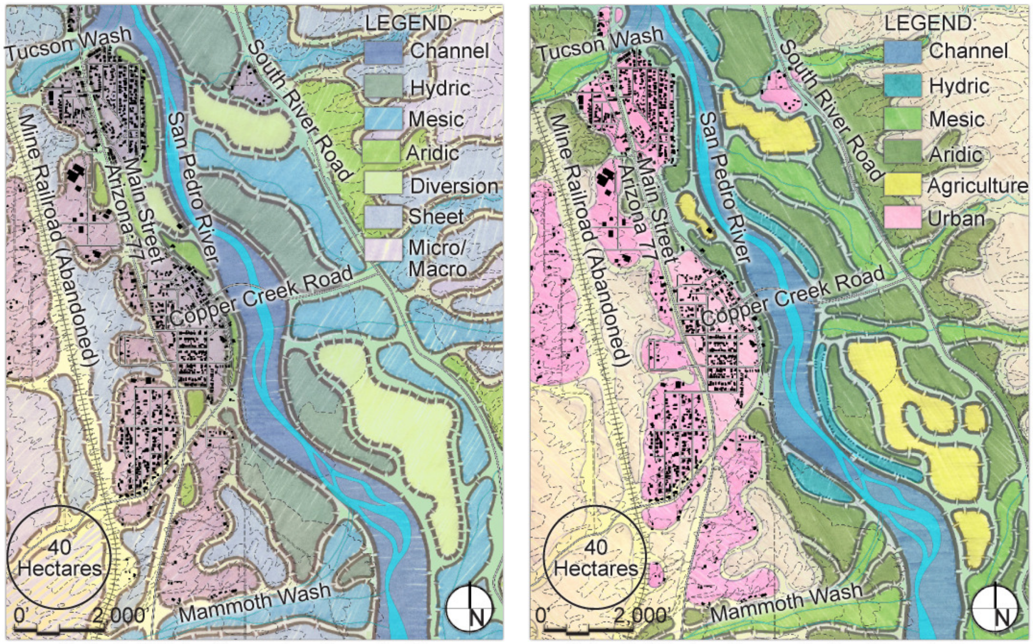


Figure 23. Proximity diagram showing local opportunities for establishing a regional park at Mammoth, Arizona.

Predicted massive growth in the Sun Corridor also means that there is an important opportunity to establish precedence for incorporating ecological processes and the built environment. This is particularly important in the context of the regional, “megapolitan-scale” development of the Sun Corridor (The

Morrison Institute, 2008), in which human impacts due to traditional designs of the built environment will result in significant damage. Preservation and restoration of critical ecosystems will provide increased benefits derived from healthy water quality, vegetative diversity, and soils while providing a basis for a regenerative landscape. In the context of this study, regenerative landscape systems "provide for continuous replacement, through its own functional processes of the energy and materials used in its operation" (Lyle, 1994, p. 10). Designing and managing the landscape and establishing natural systems restores cyclical flows of carbon by reconnecting atmospheric C-pools to long-term terrestrial carbon sinks.



Potential Water Harvesting Opportunities

Potential Carbon Sequestration Opportunities

<u>Figure 24</u>. Potential Water Harvesting and Carbon Sequestration Opportunities.

Design Interventions

This study investigates methods of estimating and analyzing the carbon capacity of dryland open space C-pools and projecting impacts of design interventions to the efficacy of carbon sequestration in generating social, economic, and environmental benefits. A project demonstrating enhanced carbon sequestration increases “uptake of atmospheric carbon dioxide during photosynthesis and the subsequent transfer of some fixed C into vegetation, detritus, and soil pools for secure storage” (Lorenz and Lal, 2010, p. 11). The degraded open spaces of the Lower San Pedro River offer ample opportunities for enhancing carbon sequestration efficacy through design interventions: restoring natural processes, conserving critical natural open spaces, and reducing future negative human impacts through integration of the built environment and natural processes.

The demonstration site is 512.84 hectares bounded on the north by the Tucson Wash and on the south by the Mammoth Wash. The Lower San Pedro River flows northward toward the Gila River directly through the center of the demonstration site. The majority of the Town of Mammoth’s built environment is included in the demonstration project to show how increased carbon sequestration efficacy can benefit social and economic conditions. There are no existing hydric (wetland) vegetative systems within the demonstration project (though they were likely present when the flow of the Lower San Pedro River was perennial). The Tucson and Mammoth washes, along with numerous unnamed ephemeral washes, are tributaries of the Lower San Pedro River during seasonal rains. An abandoned small-gauge railroad utilized for transporting copper bounds the demonstration project site to the west. Nearby, Ore Cart Trail Park and the town of Mammoth town (and mine) provide additional historical context. The South River Road and adjacent aridic vegetation form the eastern boundary of the demonstration project.

The demonstration project measures existing carbon sequestration efficacy in the degraded open space surrounding Mammoth and enhanced efficacy of a prototype design for the same open space. Efficacy of carbon sequestration is determined by analyzing short-term carbon influx and efflux in existing and proposed open spaces. Measurements of carbon sequestration efficacy for the demonstration project – dependent variables – are a measure of Mg C / ha / y of sequestered carbon. Measurements of carbon are based on the carbon typologies (hydric, mesic, aridic, biomass for energy, and biomass for agriculture) systems. General trends of carbon sequestration gains (influx) and losses (efflux) are then analyzed to determine enhanced efficacy due to design interventions (scenarios).

Enhanced carbon sequestration efficacy is determined for the demonstration project and projected to a regional-scale to determine regional-scale enhancement of carbon sequestration efficacy and potential for offsetting local human carbon sources. In this study, the findings for the demonstration project for a portion of the Lower San Pedro Watershed were applied to the entire watershed as existing conditions along the corridor generally match the existing conditions of the demonstration project. The regional-scale offset potential of the “San Pedro Regional Mitigation Corridor” were then compared to the largest local carbon source -- the Phoenix Metropolitan Area to determine the feasibility of local offsets of human carbon emissions.

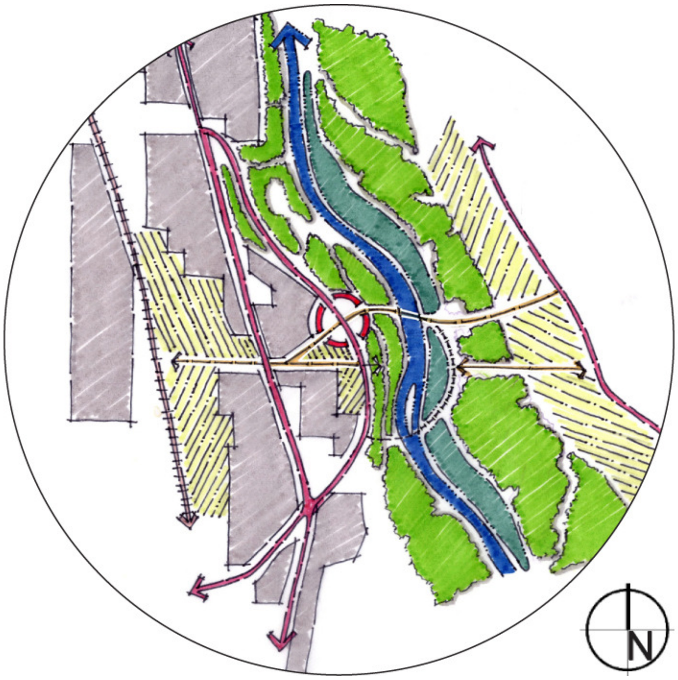


Figure 25. Partii diagram for the prototype design of Mammoth Arizona showing wetland locations, riparian area, relocated farmlands, and proposed commercial.

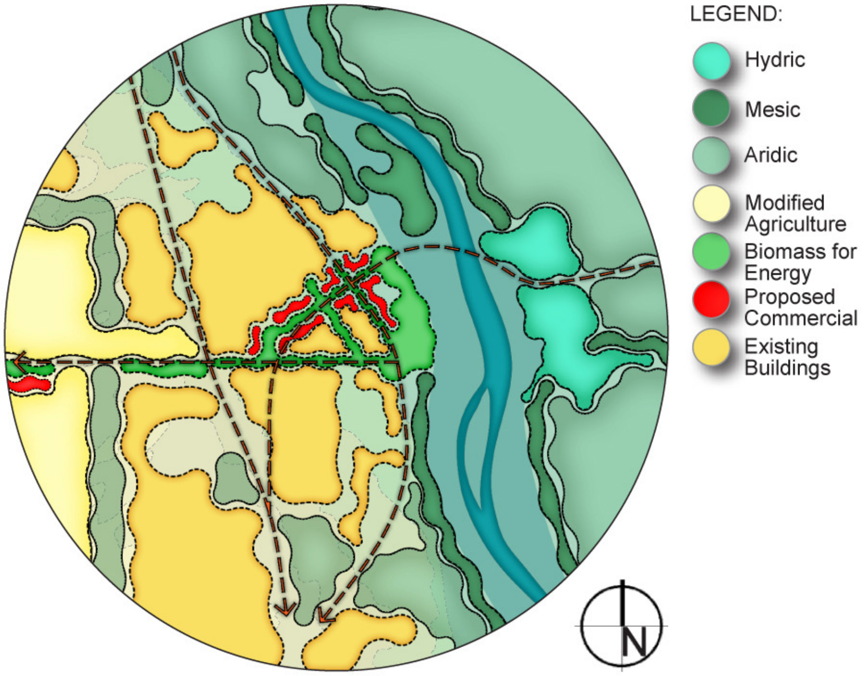


Figure 26. Concept Plan of the prototype design of Mammoth.

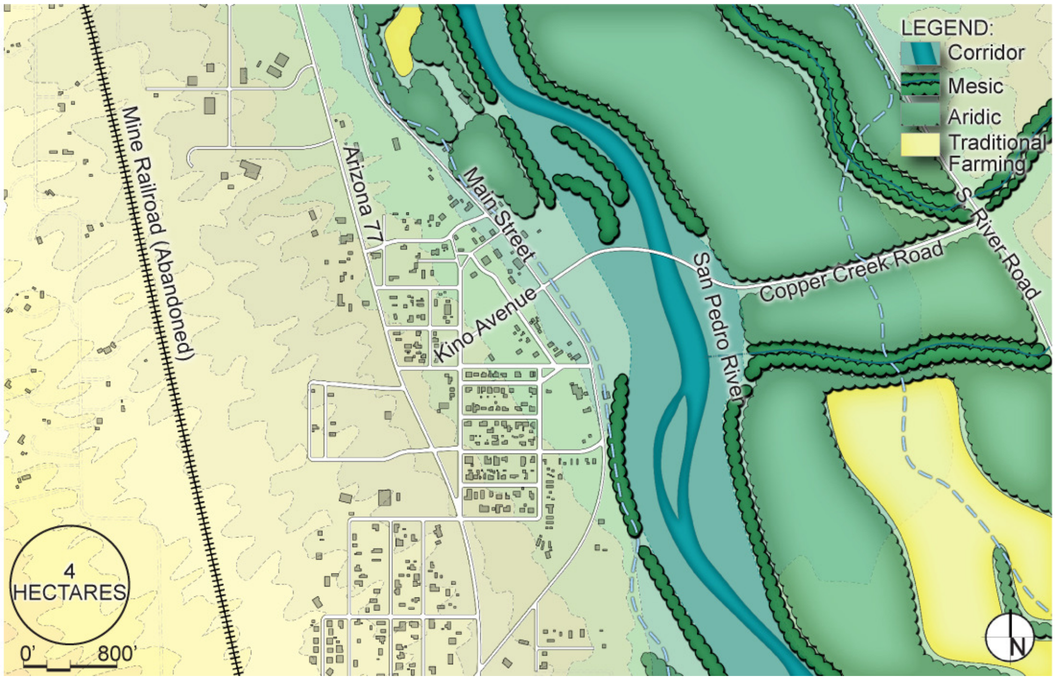


Figure 27. Existing Conditions at the Mammoth, Arizona Demonstration project.

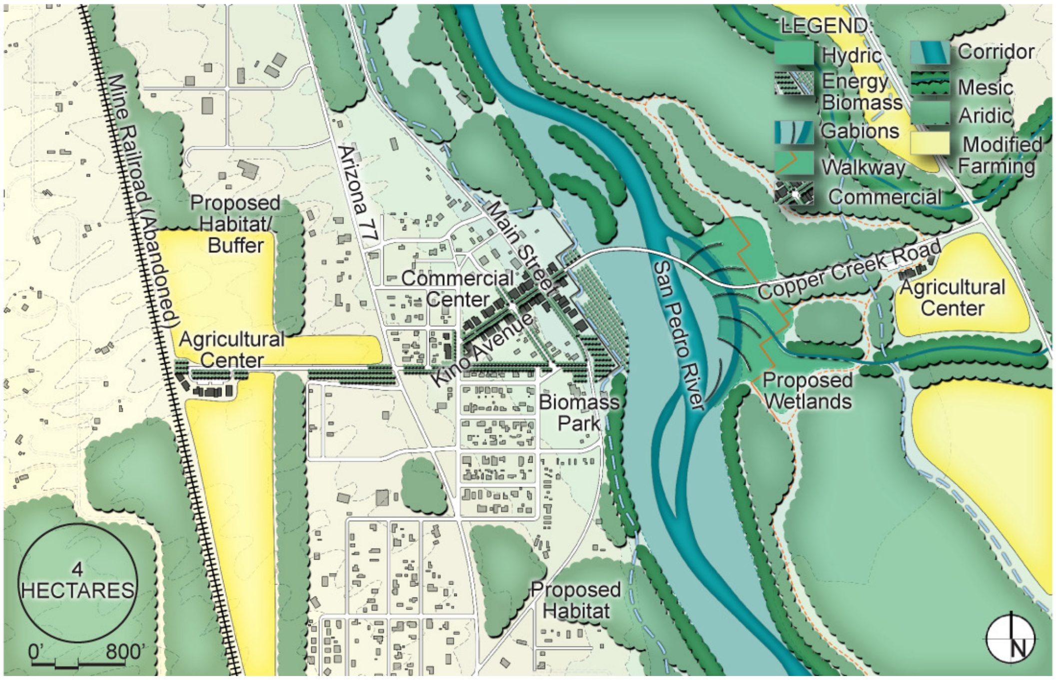


Figure 28. Proposed Conditions at the Mammoth, Arizona Demonstration project.

While there is significant interest (and potential investment) in establishing a Carbon Park, the prototype still proposes fiscally responsible investments wherever prudent. Conservation and restoration projects for improving water quality, conserving biodiversity, and protecting soils are eligible for numerous grants as well. Design proposals for the prototype design are still selected to best represent minimal investment for installation and maintenance cost of design interventions and high probable enhancement of carbon sequestration efficacy. The site-scale demonstration project must take into account a number of s limiting factors and opportunities (independent variables). Independent variables include: availability of water and ability to manipulate its course, existing and potential vegetation, soils types and use of carbon additives, and land-use (particularly agriculture).

Availability of water is the most significant limiting factor for a dryland open space carbon sequestration demonstration project. In the case of the site around Mammoth, simply restoring perennial flow to the Lower San Pedro will significantly increase the true increment of carbon sequestration efficacy in the existing mesic vegetative systems in existing riparian corridors. For this study, existing carbon sequestration efficacy is estimated with the assumption that ongoing riparian conservancy and restoration efforts to restore the Lower San Pedro are successful. This assumption is made so that prototype design carbon sequestration efficacy that also anticipate the re-establishment of healthy natural open space systems (including restored riparian corridors) do not inaccurately describes carbon sequestration enhancement from design interventions.

A hydric (wetland) vegetative system, which also greatly increases carbon sequestration efficacy, is proposed within the riparian corridor. Hydric systems have been severely impaired or destroyed along the Lower San Pedro River. The establishment of a small natural wetland is the least conservative design intervention proposed for the demonstration project. However, the efficacy of carbon sequestration in hydric systems and derived environmental and social benefits justifies the inclusion of such a systems in the prototype design. Considering the critical importance to ecological networks that the Lower San Pedro River serves to migratory birds and other wildlife, the development of wetlands in the watershed is a reasonable proposal for the demonstration project (Natural Resources Conservation Service, 2011). In the prototype design vegetative biomass is concentrated near riparian areas (the Lower San Pedro River, Tucson and Mammoth tributaries, and numerous desert washes).

It is important to note that no catchment systems shall permanently divert surface water (Arizona Revised Statute 2011, Title 45, § 141b). In the prototype project a single diversion system is proposed for the establishment of a hydric system. The demonstration project assumes that at least one diversion permit will be granted for the beneficial use – if not directly for carbon sequestration than for “wildlife including fish” which is allowed under Arizona’s water policy (Arizona Revised Statute 2011, Title 45, § 141b). Furthermore, a case can be made for the establishment of a hydric (wetlands) open space for the improvement of water quality (fixing pollutants) – certainly an arguable “beneficial use” as defined under Title 45 (Arizona Revised Statute 2011, Title 45, § 141b).

While restoring perennial water flow, hydric and mesic systems, and riparian biomass are major foci for the prototype design the demonstration project also proposes re-establishing biomass in aridic natural open spaces. Existing aridic vegetation is heavily degraded due mainly to desertification in the

Lower San Pedro watershed.   Remnants of aridic Lowland and Upland Sonoran Desert Scrub remain resilient and are enhanced in the prototype design. Aridic biomass is encouraged through native plant restoration efforts in areas of natural drainage ways (desert washes) and where rainwater catchment systems can best be utilized to overcome water constraints. Areas where rainwater is concentrated naturally and through proposed landform manipulation (tilted, rounded, sheet and micro catchments) are identified in the prototype design. The establishment of vegetative biomass is concentrated near identified areas as well as, to a lesser extent, open spaces with access to temporary irrigation.

Aridic vegetative biomass is promoted primarily through successional plant establishment but is also encouraged in open spaces where slopes and dryer conditions require the use of temporary irrigation, hyrdoseed, and initial plantings of woody plants. In particularly impaired open spaces (with temporary irrigation systems as necessary where establishment of biomass through succession is not possible at severely impaired open spaces).   Restoration (through direct planting and succession) efforts must be carefully monitored to avoid establishing invasive species that exist in the soil seed banks, such as Buffelgrass (*Pennisetum ciliare*) and Red Brome Grass (*Bromus rubens*). Once native biomass is established the demonstration project the dryland open spaces will be largely self-regenerative though maintenance will still be required at areas where human interactions occur.

Dryland soils are also a limiting variable for enhancing carbon sequestration efficacy at the demonstration project site. While aridisols (a common dryland soil type) are ideal for carbon sequestration (with deep horizons and high calcium content) other dryland soil types are less effective. The open spaces near Mammoth, particularly in areas with gradual slopes, outside the Lower San Pedro River floodplain, are predominantly aridisols. Existing vegetative biomass is designated for conservancy efforts to maximize carbon sequestration efficacy in existing systems. Re-establishing biomass is concentrated in areas where aridisols are not severely disturbed by negative human impacts. It is important to note that carbon soil sinks are significantly enhanced by carbon additives (often referred to as “injections”) – such as coal fly ash and biochar. Despite the potential for the establishment of carbon soil sinks through direct carbon injections the demonstration project does not include soil modification. Research into a carbon as a soil additive is ongoing. Use of carbon as a soil additive is not a prevailing practice in the United States. Despite significant promise for enhancing carbon sequestration efficacy, no carbon amendments to soils are proposed in the prototype design.

Lastly, many existing land-uses for the Mammoth area are not compatible with the establishment of a regenerative natural open space (the most effective open space carbon sink). The majority of the existing built environment in Mammoth would require significant expense and redesign to be integrated with regenerative open spaces required for peak carbon sequestration efficacy. While developing a truly regenerative built environment is a valuable experiment (and would require significant research and modeling advances) the viability (additional research and expense) of such project makes such an endeavor extremely unlikely. Keeping with conservative design, the demonstration project assumes that minimal efforts are made to improve the existing built environment and infrastructure with the major exception being the modifications of existing agriculture. Existing agricultural land-uses are located in critical intersections of the Lower San Pedro River and the Tucson and Mammoth Washes severely impede natural riparian processes (carbon sequestration efficacy). Traditional agriculture open spaces within critical riparian corridors are relocated (and expanded) in areas where rainwater catchment systems can bolster crop yield (opening up riparian areas for expansion of dryland biomass). Proposed agricultural lands are situated in open spaces that provide opportunities for implementing modified agricultural practices -- nontraditional land management practices that include establishment of longer harvest rotations rather than intensive short-rotation harvests, fallowing land (taking land out of agricultural use and permitting natural vegetation to restore degraded soils), future access for carbon injections (biochar and coal fly ash) not included in this study, diversified crops on plantation-style farmlands (as opposed to monoculture on industrial-scale farmland). Existing farmlands are cultivated with traditional monoculture crop rotations. The prototype design also promotes the development of agricultural soil sinks for economic growth in the region, which may potentially tie into the local eco-tourism trade by providing locally grown produce to health-and-environment-conscious visitors.

The prototype design for the Town of Mammoth and surrounding open spaces is primarily for establishing precedence for demonstrating methods of estimating and analyzing carbon sequestration in drylands. This said, proposed design interventions are viable and if implemented would significantly improve the existing environmental, social, and economic conditions. A primary focus of the prototype design is the conservation and restoration of existing and degraded dryland hydric, mesic, and aridic open spaces along the Lower San Pedro River corridor.

One of the more aggressive proposals is the establishment of a hydric (wetland) vegetative system. While the perennial flow of the Lower San Pedro created many wetland systems there are currently no wetlands near the Town of Mammoth. Restoration of perennial flows in the San Pedro will allow the establishment of wetlands once again. Utilizing water restored to the San Pedro for re-establishing a wetland system is a beneficial use under Title 45 (Arizona Revised Statute 2011, Title 45, § 141b). While providing vital habitat for wildlife (particularly migratory birds) the wetland systems can be designed to promote further water quality improvement. Wetlands naturally fix pollutants such as pollutants from agricultural runoff: nitrogen, and phosphorus (Nairn and Mitsch, 2000). Gabions are also proposed to catch sediments and heavy metal pollutants from nearby mines. The hydric system is proposed at the intersection of the San Pedro River and a major desert wash; the hydric system is within the flood plain where seasonal inundation is anticipated. A series of boardwalks provides opportunities for bird watching, education about the wetland system, and opportunities for social interaction. The wetlands are proposed in across the San Pedro River from the existing Mammoth commercial corridor on Kino Street. There are no existing hydric systems on the existing site. The prototype design proposes 7.85 hectares of wetlands. Dryland hydric open spaces have high soil carbon sequestration efficacy of 1.40-2.63 Mg C / ha / y (Adhikari *et al.,* 2009). Including dryland hydric biomass influx (estimated at 2-3 Mg C / ha / y) hydric open spaces in dryland have a carbon influx of roughly 3.40-6.63 Mg C / ha / y (Lal, 2004). Wetlands in more temperate areas would have significantly higher carbon sequestration efficacy due to perennial biomass. Even the relatively small proposed wetlands of 7.85 hectares the hydric system would generate approximately 26.69-52.05 Mg C / y.

Re-establishing natural vegetative conditions is necessary for enhancing carbon sequestration efficacy is accomplished by shifting existing agricultural lands away from the floodplain. Agricultural lands are relocated to areas where water constraints can be overcome through the concentration and harvesting of rainwater. Existing mesic vegetation is conserved and, where degraded, restoration is proposed for the San Pedro River and desert washes. Mesic systems are protected by the introduction of aridic buffers (150-200' width). These buffers mitigate potential human impacts (manly from adjacent agricultural fields) to critical carbon sequestration open space systems. Mesic systems, like hydric systems, have generally high carbon sequestration efficacy ranging between 2.04-3.06 Mg C / ha / y (Lal, 2004, p. 537). Low ranges include loss of carbon embodied in soil and vegetation due to natural levels of erosion. There are 32.94 hectares of existing mesic systems in the demonstration project; these open spaces are heavily degraded systems but still have carbon influx of 67.20-100.80 Mg C / y (with carbon influx more likely to be a low range estimate). Restoration of mesic systems are proposed in the prototype design but the total mesic system is slightly smaller due to the introduction of the proposed hydric open space. Proposed restoration of biomass and diversity coupled with linking existing open spaces will create more resilient and much more efficient mesic open spaces than the existing system. The proposed mesic system is 28.53 hectares and estimated to have carbon influx of 58.20-87.30 Mg C / y (with carbon influx more likely to be a high range estimate).

The largest existing natural open spaces in the San Pedro Carbon Park are aridic dryland systems comprised of Upland and Lowland Desert Scrub vegetation comprised of large cacti, tall tree-like shrubs, and trees; commonly, Mesquites (*Prosopis spp.),* Thorntrees (*Acacia spp.*), and Ironwoods (O*lneya tesota)* (Brown and Lowe, 1978). Carbon sequestration efficacy is based typical average cover consisting of large hardwood tree species that comprise much of the biomass of open space systems in the San Pedro River demonstration site. While the assumed biomass has carbon influx of 2.04-2.06 Mg C / ha / y (Lal, 2004) though drier areas of desert scrub may have an average carbon influx of as little as 0.002-0.004 Mg C / ha / y) (Lal, 2004, Glenn *et al.*, 1993). This study assumes that with the restoration of perennial flow to the San Pedro River that larger biomasses can be established similar to the high biomasses of less disturbed open spaces further north where the San Pedro and Gila Rivers converge. There are 138.81 hectares of existing, heavily degraded aridic open space in the Mammoth demonstration project that have a carbon influx of 283.18-424.77 Mg C / y. Design interventions propose concentration of rainwater through landform manipulation. Woody plants are established in areas where water and water-borne nutrients in sediments are concentrated. In the demonstration project, an additional 44.23 hectares of aridic open space restoration is proposed – for a total of 183.06 hectares. Aridic open space in the prototype design is estimated to have a carbon influx of 373.41-560.12 Mg C / y.

Existing agricultural lands in the demonstration project are located in the floodplain of the San Pedro River and severely fragment the open spaces and impair natural water flow from tributaries. Observed management of existing agriculture fields – traditional monoculture crop rotations of hay and cotton –

result in seasonal carbon efflux (loss) from soils disturbed during harvest events. Existing agriculture is the second-most prevalent land-use in the demonstration project accounting for 28.81 hectares of the existing site. Existing traditional agriculture is also has very low carbon sequestration efficacy. Carbon efflux during planting and harvest is less than carbon influx utilizing traditional methods (Lal, 2004). Existing agricultural systems are carbon sources rather than sinks' this study assumes that existing carbon sequestration for existing farmlands is 0.00 Mg C / y.

The prototype project proposes modified agricultural processes in an effort to create viable agricultural soils as a carbon sink rather than source. Modified agricultural practices are proposed on new sites with future access to carbon injections (bio-char and carbon fly ash) brought from the nearest coal-fire plant in Tucson and biochar from potential byproducts of biomass from surrounding communities to produce energy. Agricultural soil sinks developed with carbon additives are not proposed in the prototype design. Even without carbon soil additives, modified agricultural practices such as establishment of longer harvest rotations, fallowing land (taking land out of agricultural use and permitting natural vegetation to restore degraded soils), polyculture (or permaculture), and locally owned plantations utilizing low-impact practices and technologies. However, modifications in agricultural practices increase can in create carbon sinks (instead of sources) with enhanced carbon sequestration rates observed between 0.08 and 0.10 Mg / ha / y (Lal, 2004, p. 537).

This study also assumes that as the Sun Corridor expands and a single megalopolis is formed between Phoenix and Tucson along with associated population growth demand for access to natural open spaces will increase bringing additional opportunities to Mammoth and surrounding communities. While agriculture is inherently not a regenerative process, more sustainable practices capitalizing on concentrated rainwater and rainwater harvesting to overcome water constraints could potentially become Mammoth's new lease on life. The prototype project includes proposals for greatly increasing agricultural farmlands (from 28.81 hectares to 66.66 hectares) while utilizing modified agricultural practices to create a farmland carbon sink of 5.30-6.66 Mg C / year.

Biomass for energy holds much promise for reducing reliance on fossil fuels. Large metropolitan areas, such as the Greater Phoenix Metro Area and the City of Tucson could potentially generate demand for renewable energy sources in the form of biomass. The demonstration project anticipates that some portion of future energy demand may be met by biomass for energy production. 4.25 hectares of land are reserved in the prototype design to highlight the potential for biomass for energy. While the specifics for the development of a biomass for energy production system are not explore in this study the carbon sequestration efficacy of biomass for energy plantations are. A small biomass for energy offset is situated in proximity to Mammoth's existing commercial district where it can act as a public open space with access to San Pedro River (which will be considerably more valuable once perennial flow is restored in the Lower San Pedro). Biofuel production for direct combustion has a carbon sequestration rate of 2.00-3.00 Mg / ha / y (Lal, 2004, p. 537). Assuming an average cover of large woody biomass (which, is not wholly harvested) for biofuel the carbon sequestration for the parcel would be approximately 8.50-12.75 Mg / ha / y.

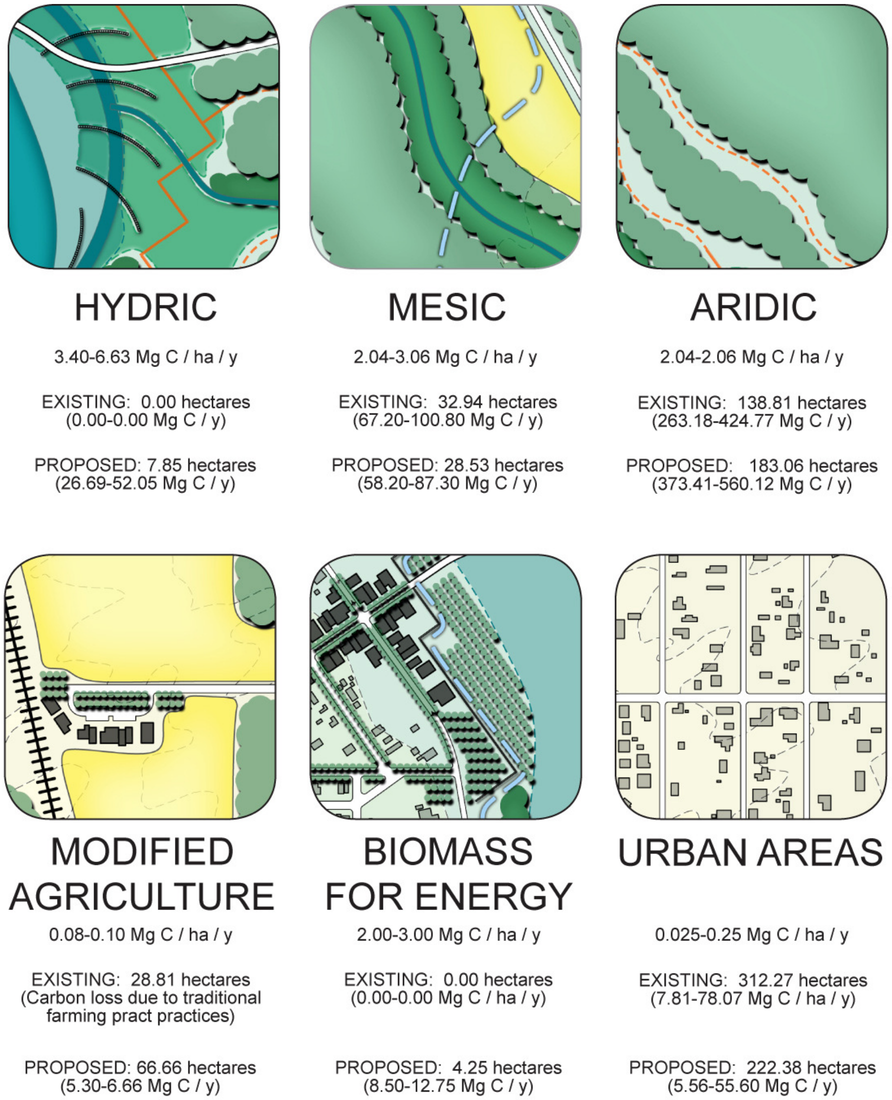
The various proposals included in the prototype project will potentially greatly benefit the Town of Mammoth. Potential urban growth / rehabilitation of existing privately owned properties in Mammoth provide an opportunity for developing a truly regenerative built environment. However, the complexities of designing such a system coupled with associated investments are not anticipated. In this study, the existing and proposed urban environments are assumed to offer low carbon sequestration efficacy roughly 0.025 and 0.25 tons of C / hectare / year with minimal overall sequestration enhancement (or loss) for the demonstration project. Additional research is necessary to determine the true increment of urbanized areas. This proposed number for the true increment of urbanized areas takes into account that there is little or no litterfall in urbanized area, and assumes minimal formation of secondary carbonates (Lal, 2003).

Figure 29. Sketches of design proposals: biomass for energy park, commercial center at Kino Street, and boardwalks at the proposed wetlands.

While the urban environments may not enhance carbon sequestration, the built environment is still included as a critical piece of the San Pedro Carbon Park A revised commercial center centered on the existing dilapidated and abandoned commercial areas on Kino Street is proposed as well as two local agricultural centers where produce can be marketed to future tourists from the Sun Corridor. The proposed design interventions –hydric, mesic, and aridic natural open space restoration and conservation and agricultural and commercial centers – will provide a destination for future populations in the Sun Corridor as well as education opportunities for learning about the benefits of enhancing carbon sequestration efficacy. In this study, the existing and proposed urban environments are assumed to offer low carbon sequestration efficacy roughly 0.025 and 0.25 MG C / ha / y with minimal overall sequestration enhancement (or loss) for the demonstration project. Low amount of carbon transfer from aboveground biomass to belowground biomass from litterfall is assumed. Existing urbanized area account for 312.27 hectares of the existing site; these areas have a low carbon sequestration efficacy of roughly 7.81-78.07 Mg C / y. The prototype design reduces the total area of urbanized areas by restoring brownfield with successional aridic planting, demolishing abandoned structures within the floodplain, and proposing desert restoration projects on vacant lots. The prototype design reduces the urbanized areas to 222.38 hectares with a carbon sequestration of 5.56-55.60 Mg C / y.

The base case established for the 512.84-hectare demonstration site took into account existing land-uses and conditions. Efficacy for the existing conditions is likely less than estimated due to assumptions designed to establish measurement of regional-scale carbon sequestration. First, restoration of historical perennial flow of water to the Lower San Pedro mesic systems is assumed. Without restoration of historical flows mesic systems in the Lower San Pedro River will continue to deteriorate along with carbon sequestration. The prototype design anticipates no further degradation of the existing open spaces. Secondly, the existing open spaces of the Lower San Pedro are being further degraded due to continued human impacts – particularly desertification due to human water use and ongoing damage to the low-water channels of the San

Pedro River and local washes due to off road vehicles. The prototype project anticipates that conservancy efforts to preserve natural habitats within the San Pedro Watershed are successful Thus, existing open space systems are assumed to have been restored from their current degraded condition and sequester more carbon than they currently do. These assumptions are applied to the existing conditions so that site conditions (and ongoing efforts to restore the site) do not misrepresent carbon sequestration efficacy enhancements due to design interventions. Ultimately, carbon efficacy measurements for this study will be very conservative.



HYDRIC

3.40-6.63 Mg C / ha / y

EXISTING: 0.00 hectares
(0.00-0.00 Mg C / y)

PROPOSED: 7.85 hectares
(26.69-52.05 Mg C / y)

MESIC

2.04-3.06 Mg C / ha / y

EXISTING: 32.94 hectares
(67.20-100.80 Mg C / y)

PROPOSED: 28.53 hectares
(58.20-87.30 Mg C / y)

ARIDIC

2.04-2.06 Mg C / ha / y

EXISTING: 138.81 hectares
(263.18-424.77 Mg C / y)

PROPOSED: 183.06 hectares
(373.41-560.12 Mg C / y)

MODIFIED AGRICULTURE

0.08-0.10 Mg C / ha / y

EXISTING: 28.81 hectares
(Carbon loss due to traditional
farming pract practices)

PROPOSED: 66.66 hectares
(5.30-6.66 Mg C / y)

BIOMASS FOR ENERGY

2.00-3.00 Mg C / ha / y

EXISTING: 0.00 hectares
(0.00-0.00 Mg C / ha / y)

PROPOSED: 4.25 hectares
(8.50-12.75 Mg C / y)

URBAN AREAS

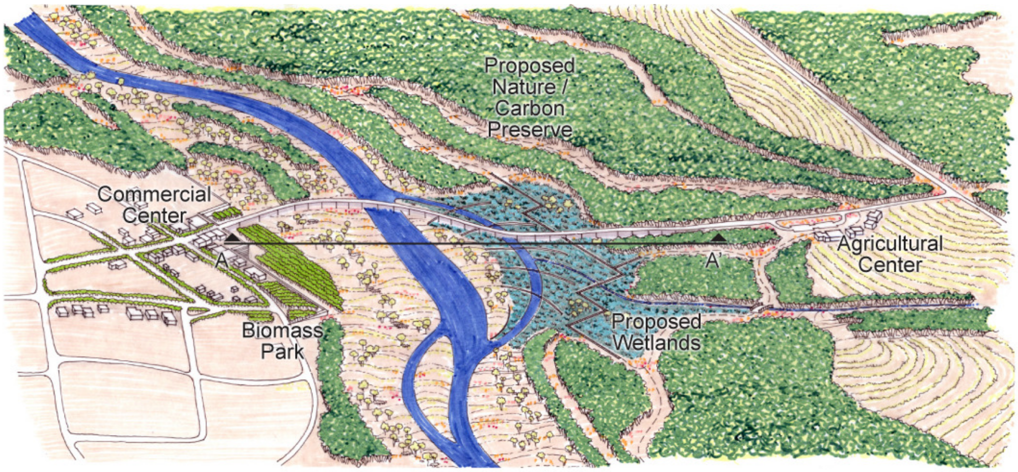
0.025-0.25 Mg C / ha / y

EXISTING: 312.27 hectares
(7.81-78.07 Mg C / ha / y)

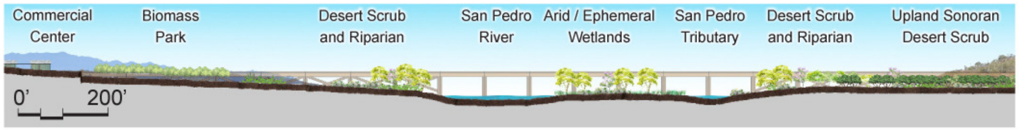
PROPOSED: 222.38 hectares
(5.56-55.60 Mg C / y)

Figure 30. Summary of carbon sequestration by existing and proposed land uses.

Existing carbon sequestration efficacy is estimated to be 358.18-603.63 Mg C / y for demonstration project site of 512.84 hectares (or 0.70 and 1.18 Mg C / ha / y). Existing natural mesic and aridic open spaces sequestered the majority of carbon in the existing conditions analysis accounting for 350.37-525.56 Mg C / y (or 87-97 percent of open space carbon influx for the site). The prototype design for the demonstration site projected significant gains in carbon sequestration efficacy due to design interventions. Total carbon sequestration efficacy was estimated to be 477.69-774.47 Mg C / year (or 0.93-1.51 Mg C / ha / y). Gains in carbon sequestration were significant due to the introduction of a hydric open space, restoration of degraded aridic open spaces, and modification of the existing agricultural systems resulted in the increased carbon sequestration efficacy. The most significant carbon efficacy enhancements were made through the restoration of a hydric system (7.85-26.69 Mg C / y) and restoration of degraded aridic open spaces (373.41-560.12 Mg C / y). The prototype design is predicted to have 128-133% enhanced carbon sequestration over existing conditions over 40 years until the dryland open spaces reach a steady state.



Perspective of the San Pedro Carbon Park



Section of the San Pedro Carbon Park (A-A')

Figure 31. Perspective and section of the proposed Lower San Pedro Carbon Park at Mammoth, Arizona.

EXISTING LAND USE
(Carbon Sequestration Mg C / ha / yr)

CARBON TYPOLOGY	SIZE (ha)	Carbon equestered (Mg C / y)
Hydric	0.00	0.00 - 0.00
Mesic	32.94	67.20 - 100.80
Aridic	138.94	263.18 - 424.77
Agriculture (Traditional)	28.81	0.00 - 0.00
Agriculture (Energy)	0.00	0.00 - 0.00
Urban	312.27	7.81 - 78.07
TOTAL	512.84	358.18 - 603.63

PROTOTYPE LAND USE
(Carbon Sequestration Mg C / ha / yr)

CARBON TYPOLOGY	SIZE (ha)	Carbon equestered (Mg C / y)
Hydric	7.85	26.69 - 52.05
Mesic	28.53	58.20 - 87.30
Aridic	183.06	373.41 - 560.12
Agriculture (Modified)	66.66	5.30 - 6.66
Agriculture (Energy)	4.25	8.50 - 12.75
Urban	222.38	5.56 - 55.90
TOTAL	512.84	477.69 - 774.47

Figure 32. Summary of carbon sequestration efficacy measurements for the demonstration project existing conditions and prototype design.

The demonstration project suggests that enhancing carbon sequestration efficacy can be estimated and predicted by designers utilizing research of natural processes. Enhanced carbon sequestration estimated in the prototype design can be applied to similar base conditions of the watershed where water constraints, vegetation, soils, and land-uses (including natural open space degradation) are similar conditions. Along the Lower San Pedro Watershed, open spaces with similar existing conditions to the demonstration project total 39,311.34 hectares. With an existing sequestration efficacy estimated at 0.70 and 1.18 Mg C / ha / y, total carbon influx for the similar conditions located along the Lower San Pedro River corridor are estimated to have carbon sequestration of approximately 27,456.07-46,270.63 Mg C / ha / y. By applying similar design interventions along the designated open spaces the watershed's carbon sequestration efficacy would increase to 0.93-1.51 Mg C / ha / y for total carbon sequestration of 36,617.19-59,366.59 Mg C / ha / y. Potential regional carbon sequestration for the Lower San Pedro River watershed would make an ideal local offset project – a possible “regional carbon mitigation corridor”.

The San Pedro Regional Carbon Mitigation Corridor has the potential to sequester 36,617.19-59,366.59 Mg C / ha / y. This potential carbon influx is sustained as restored natural open space biomass recover and grow toward a steady state. After approximately 40 years when equilibrium is attained – biomass growth is only slightly higher than biomass loss – then carbon sequestration efficacy in vegetation drops significantly (carbon influx is nearly equal to carbon efflux) (Schlesinger, 1997). Long-term carbon sequestration in soils through the formation of secondary carbonates transfers carbon in the atmosphere to more stable states in terrestrial carbon sinks so these open space systems are still mitigate negative climate change while providing other benefits of natural open space. Potential benefits of the San Pedro Regional Carbon Mitigation Corridor are many but include: negative climate change mitigation, improved water quality, increased biodiversity, and opportunities for agricultural biomass.

Regional carbon offset projects in dryland open spaces are only a small part of the solution reducing human impacts to the carbon biogeochemical cycle. The Phoenix Metro Area is a massive carbon source with estimated carbon dioxide emissions for City of Phoenix Operations alone of 618,682 Mg C / y (NETL, 2007; Local Governments for Sustainability, 2009. p. 3). Additional regional carbon overburden will result from human impacts to existing open spaces of the Sun Corridor along with increased energy demands for the proposed population and urban growth.

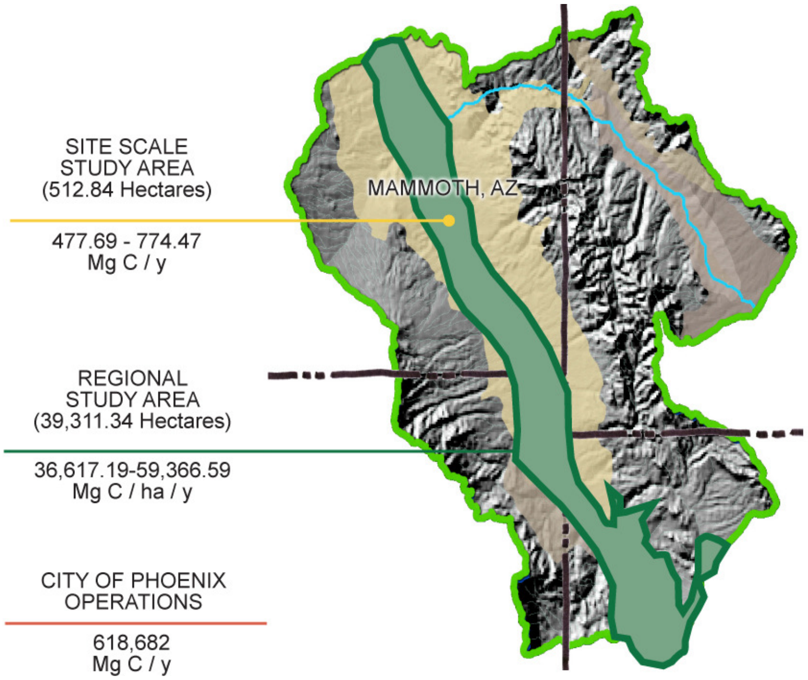


Figure 33. Location of the Mammoth Demonstration Project and the proposed San Pedro Regional Carbon Mitigation Corridor.

At peak efficiency, the San Pedro River Corridor Regional only sequesters 5.9-9.6% of the carbon emissions of the city of Phoenix governmental buildings – a fraction of the entire Phoenix Metropolitan Area/'s carbon footprint. Drastic reductions in overall carbon footprint in the Sun Corridor would be required for local carbon offset projects, like the San Pedro Regional Carbon Mitigation Corridor, to be a viable option for balancing emissions. Estimating and analyzing carbon sequestration confirms that while open space sinks are valuable enhanced carbon sequestration only slows down human impacts to the biogeochemical carbon cycle -- new technologies and design processes are necessary to ensure carbon equilibrium (Lorenz and Lal, 2010).

Chapter 5

DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

Discussion

Enhanced carbon sequestration efficacy only slows down human impacts to the biogeochemical carbon cycle. The development of natural open spaces as carbon sinks are already being established as an option for companies, organizations, and individuals with a desire to reduce their carbon footprint (Great Britain Forestry Commission, 2011). Increasing carbon sequestration in open spaces is only part of the solution to mitigate negative climate change. Development of offset programs (such as establishing industrial and natural carbon sinks) in order to justify ever-growing carbon footprints is not a sustainable solution to carbon overburden. Decreasing carbon in the atmospheric C-pool must be accomplished in tandem with overall reductions in carbon footprints -- particularly by reducing reliance on fossil fuels. Understanding of ecological processes and the benefits and constraints of offsetting human carbon sources highlights the importance of long-term residence of carbon in biotic and pedologic C-pools. Incorporating natural processes leads to more efficient designs incorporating the built environment and ecological systems. Design literature lauding the benefits of open space carbon sequestration as a benefit of open space carbon sinks (including street trees, urban parks, green roofs, and other temporary biomasses) highlight the carbon influx without considering efflux or achievement of steady states in vegetation. Designers who do not understand carbon efflux and steady state in open space systems will erroneously assume that carbon sequestration benefits of open spaces are significantly higher than they really are. Furthermore, natural geologic-scale exchange of carbon takes place after tens-of-thousands of years – a life cycle that cannot be accelerated through current technologies and design interventions.

Conclusions

Carbon sequestration can be estimated and enhanced by incorporating ecological processes into design of the built environment. However, contrary to common understanding in design-related fields, the climate change mitigation benefits of carbon sequestration are relatively small after biomass has matured and reached a steady state. Net photosynthesis (when carbon is debited from the atmosphere) is matched by net respiration credited back to the atmosphere through leaves, trunk, stems, and roots, or carbon (Allen and Lemon, 1976). Ultimately, plant communities achieve equilibrium (or steady state) in living biomass when allocation of woody tissue is balanced by death and loss of older parts (Schlesinger, 1997). However, there is a short period of time (an average of 40 years) where new plant communities produce biomass at a much faster rate than production of dead material (Schlesinger, 1997). In steady state biomass the majority of carbon sequestered in above-and-belowground biomass immediately effluxes back to the atmosphere C-pool through vegetation and soil respiration. Open spaces in equilibrium, especially if they have significant biomass are extremely efficient at exchanging carbon; only a small fraction of carbon debited from atmospheric C-pools is not immediately credited through vegetative and soil respiration (Allen and Lemon, 1976). To maintain consistent climate change mitigation benefits (debits from the atmospheric C-pool), new open spaces will have to be continually established while existing open space carbon sinks are preserved.

Not all carbon sequestered in above and belowground biomass returns to the atmosphere through plant and soil respiration and decomposition. Some fraction of net primary productivity (NPP) is lost to herbivores and in the death and loss of plant tissue; known collectively as litterfall (Schlesinger, 1997). Soil organic matter (SOM) accumulation is a measure of NPP (expressed in units of grams of C / square meter / year). In dryland ecosystems carbon reacts with calcium to form pedogenical (or secondary) carbonates. The formation of secondary carbonates and other soil inorganic carbon (SIC) are more stable than organic carbon and can sequester substantial amounts of carbon (Mermut and Landi, 2006). Secondary carbonates are found in relatively dry soils and developed under natural good drainage and vegetation comprising grass and shrub mixtures (Mermut and Landi, 2006). Secondary carbonates occur in dryland soils as calcite and magnesium calcite deposits on lower surfaces pebbles and complex, layered structures under cobble common in arid climates (Mermut and Landi, 2006).

Calcium carbonate "is a common secondary carbonate found in desert ecosystems and form calcic horizons in soils via limited weathering and leaching of the soil profile" (Schlesinger, 1997 p. 115). Calcic horizons can be greater than 10,000 years old and calcium carbonate has accumulated at rates of 1-5 g C / m^2 / y from the downward transport of Ca-rich minerals deposited from the atmosphere (Schlesinger, 1997, p. 115). The addition of both above-and-below ground biomass increases the amount of soil organic carbon (SOC) in an open space system. There is a strong synergistic interaction between biomass and

SOC and secondary carbonates (Lorenz and Lal, 2003). Designers can help maintain soil carbon sinks by reducing project limits of disturbance to existing vegetation and soils.

Global potential of carbon sequestration in dryland ecosystems is large -- Dryland regions cover about 47.2% of the terrestrial land area or about 6.15 billion hectares (Schlesinger, 1997, p. 135). 5.6% of the terrestrial land area in North American alone (Middleton and Thomas, 1992; Noin and Clarke, 1997; Reynolds and Smith, 2002; and Lal, 2003). For example, tentative calculations based on land area multiplied by improved land-uses [afforestation with Mesquite (*Prosopis spp)* and Thorntrees (*Acacia spp.)* in dryland open spaces of the United States Southwest] would lead to increased carbon sequestration efficacy (Lal, 2003). The biggest potential benefit of understanding the process of carbon sequestration and carbon flux is that it highlights the value of conserving existing natural open spaces -- the most efficient carbon sinks.

Impaired systems are never in equilibrium and disturbed open spaces are potentially important local carbon sinks (Lal and Lorenz, 2009). Design interventions and conservancy efforts at a regional-scale have a number of benefits: preservation and restoration of biomass, reduction in erosion and pollution, and limiting incompatible land-uses significantly curtails carbon loss and encourages sequestration in remnant ecosystems. Natural open space conservation efforts would be supported by quantification and increasing value-added to open space project by carbon mitigation. Carbon offset values currently ranges between $1 per metric ton in the United States and $99 per metric ton in Switzerland) (Chicago Climate Exchange, 2011). These values do not come close to representing damages caused by global climate change due to overburden of the carbon cycle.

Conservancy of existing open spaces is also important because there is potential that existing undisturbed vegetation may sequester significant amounts of carbon dioxide and potentially offset global fossil fuels and deforestation (Schlesinger, 1997; Idso and Kimball, 1993). Due to increasing concentrations of carbon dioxide in the atmospheric C-pool, plants are beginning to undergo stimulated photosynthesis. Studies suggest that plants may potentially absorb an additional 40% more carbon when carbon dioxide [concentrations are] double ambient values (Schlesinger, 1997). Increased carbon dioxide concentrations may also increase water-use efficiency in vegetation due to partially closed stoma, which would result in moister soils (Schlesinger, 1997). It is suggested that human impacts to the global biogeochemical cycle will culminate in conditions similar to the Carboniferous Period -- high atmospheric carbon dioxide, larger biomass, and moister soils (Schlesinger, 1997).

Riparian and wetland open space systems are particularly important to dryland biogeochemical processes. Prior to human impacts, riparian and wetland systems connecting many streams and rivers had increased capacity to maintain critical geochemical balances, particularly in regard to carbon (C), nitrogen (N), and phosphorus (P) (Nairn and Mitsch, 2000). Water quality is increased due to vegetative biosynthesis (or fixation) of pollutants -- such as nitrogen and phosphorus. Wetland and Riparian zones are particularly effective at removing agricultural and industrial nitrogen and phosphorus pollutants from water. Nitrogen is consumed by denitrifying bacteria found in abundance in riparian and wetland systems, which convert nitrate to inert dinitrogen gas.

Carbon supplies adequate for bacterial respiration (SOM-rich detritus) enhance denitrification processes. “Little vegetative biomass may not provide sufficient stocks of organic material for microbial denitrifiers” (Mayer *et al.,* 2006, p. 3). Furthermore, wetlands effectively improve riparian water quality by retaining phosphorus (P) and decreasing turbidity. Wetlands act as effective sinks for total and dissolved reactive P. These P sinks are substantially influenced by biological uptake and chemical reactions with the secondary carbonate calcium carbonate (Nairn and Mitsch, p. 123). Riparian and wetland restoration projects can be designed to sequester significant amounts of carbon while improving water quality.

Organisms regulate the flux of carbon between atmosphere and the biosphere through primary production and decomposition (hence “bio” in biogeochemical cycles). The key to ecosystem functioning “is the transfer of energy and carbon from producers (trees) to consumers (animals) and decomposers (microorganisms)” (Lal and Lorenz, 2009, p 5). There is a strong synergistic relationship between carbon sequestration and biodiversity -- enhancing the efficacy of carbon sequestration provides additional opportunities for above and belowground biomass (such as habitat creation). Carbon sequestration and biodiversity are often interchangeable terms in some scientific literature. Since all animal life depends on the productivity of plants, the number of animal species tends to increase as plant productivity increases (Huston and Marland, 2002). A widely observed pattern of plant diversity, first described by Grime, is an increase from low levels of diversity under conditions of very low productivity to a maximum at intermediate levels of productivity and then a decrease to relatively low levels where productivity is highest (Huston and

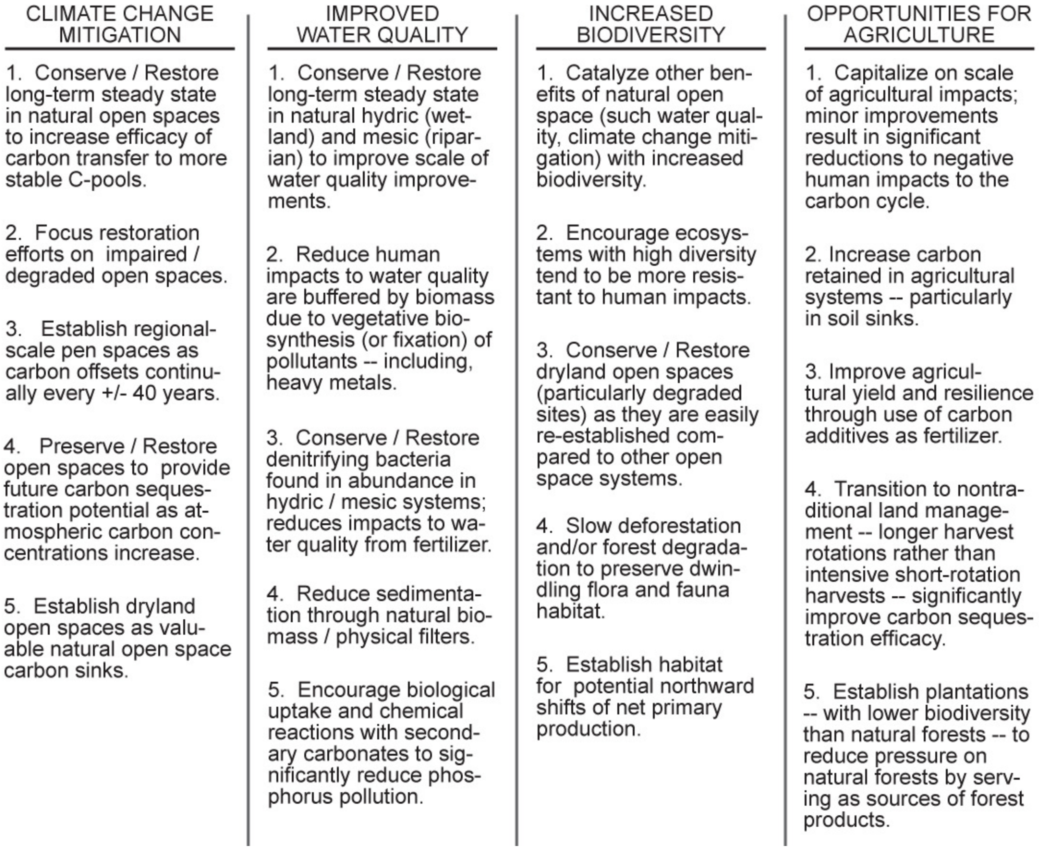
Marland, 2002; Grime, 1979). “Ecosystems with many species are not necessarily more productive than ecosystems with few species; yet, ecosystems with high diversity tend to be more resistant to human impacts” (Huston and Marland, 2002, p.. 78). The consequences of human land-use on biodiversity have been mitigated by the natural patterns of plant diversity, which includes lower biodiversity on the most productive lands. “As impacts from human land-use intensify lessened biodiversity can be mitigated further by awareness, understanding, and appropriate land-management strategies” (Huston and Marland, 2002, p. 81). Dryland ecosystems with relatively low productivity due to water constraints tend to have surprisingly high biodiversity. Restoration and conservancy efforts in dryland open spaces promote species diversity and resilience to future human impacts while serving as long-term carbon reservoirs.

In addition to climate change mitigation benefits, slowing deforestation and/or forest degradation (including desertification in drylands) provides substantial biodiversity benefits (IPCC, 2002). Often overlooked is the importance of healthy soils where sizable amounts of carbon flux occur in microbial communities and belowground biomass – “roots”. “Secondary carbonates precipitate into dryland soils in steady state, or mature, biomass through root respiration“ (Schlesinger, 1997, p. 115). The effect of humans on biomass and NPP is reflected by changes in the global carbon cycle and in the composition of the atmosphere (Schlesinger, 1997). While potentially increasing the efficacy of vegetation carbon sinks; climate change due to increased atmospheric concentrations of carbon dioxide and associated infrared reflection due to GHGs will also “result in a massive northward shift of net primary production” (Schlesinger, 1997, p. 149). Interestingly, elevated carbon dioxide concentrations could increase water-use efficiency of vegetation due to partial closing of stoma (Schlesinger, 1997) The general effect of projected human-induced climate change is that the habitats of many species will move pole ward or upward from their current locations (IPCC, 2002; Schlesinger, 1997). Habitat restoration and conservation projects will have to take into account global shifts in species populations.

"The direct harvest of plants for food, fuel, and shelter account[s] for about 6% of worldwide terrestrial productivity" (Schlesinger, 1997, p. 147). The biotic C-pool performs the economic functions of agricultural and forest productivity and as such these functions are a "subset of the carbon cycle processes that sustain all life on earth" (Huston and Marland, 2002, p.78). The rate of carbon accumulation in traditional agriculture systems does not equal the rate of carbon loss during harvest (Schlesinger, 1997). Improving the efficacy of dryland carbon sequestration through modified agricultural practices enhances economic functions including improved crop yield (for bio-fuels, food, and production) while potentially providing important vegetative and soil carbon sinks. Nontraditional land management practices include establishing longer harvest rotations rather than intensive short-rotation harvests, carbon injections (biochar and coal fly ash), diversified crops on plantations (as opposed to monoculture on industrial-scale farms) and fallowing land (taking land out of agricultural use and permitting natural vegetation to restore degraded soils).

Agricultural soils can also be effectively managed to act as carbon sinks by reducing impacts to soils during harvest. Though the amount of carbon sequestered is relatively small, holistic agriculture adoption of practices encouraging carbon sequestration could create a significant open space carbon sink. When used as a soil additive, carbon fly ash, a byproduct of coal combustion, can significantly increase soil C sequestration (Amonette *et al.,* 2000). If some of the harvested material is stored as long-lived products such as construction lumber, the stock of carbon stored in products will increase with time (Huston and Marland, 2002). Increases in biotic growth due to the availability of carbon additives are temporary. Increased growth of biota in soils where availability of carbon is no longer a limiting factor is ultimately limited by availability of other soil nutrients. In dryland agricultural systems, carbon injections in the form of biochar and carbon fly ash as fertilizer significantly enhance soil fertility and the formation of secondary carbonates on a temporary basis. Even without soil injections, biomass products generally require less fossil-fuel energy for their production and use than plastic and metal products they substitute.

Replacing fossil fuels and other products with bio-products has significant potential to utilize the biotic C-pool to reduce the carbon dioxide concentration of the atmosphere (Huston and Marland, 2002). Biomass energy use reduces net carbon emissions by displacing the use of fossil fuels while mitigating the negative local impacts of fossil fuel combustion and mining. While industrial-scale monoculture plantations will have significant negative impacts on biodiversity and water use, small-scale multi-cultural biomass for energy sites with set-asides for native flora and fauna may be a viable alternative to fossil fuel (IPCC, 2002). For example, plantations -- with lower biodiversity than natural forests -- can reduce pressure on natural forests by serving as sources of forest products, thereby leaving greater areas for biodiversity and other environmental services (IPCC, 2002). Biofuel plantations generally have higher animal biodiversity than do the annual agricultural systems they replace (largely because of the longer harvest intervals and greater physical structure), but lower biodiversity than natural forest stands in the same environments (Huston and Marland, 2002; Cook and Beyea, 2000). Modifying traditional agricultural practices alone can reduce carbon burden and begin to mitigate negative climate change and promote a carbon neutral future.



CLIMATE CHANGE MITIGATION	IMPROVED WATER QUALITY	INCREASED BIODIVERSITY	OPPORTUNITIES FOR AGRICULTURE
1. Conserve / Restore long-term steady state in natural open spaces to increase efficacy of carbon transfer to more stable C-pools.	1. Conserve / Restore long-term steady state in natural hydric (wetland) and mesic (riparian) to improve scale of water quality improvements.	1. Catalyze other benefits of natural open space (such water quality, climate change mitigation) with increased biodiversity.	1. Capitalize on scale of agricultural impacts; minor improvements result in significant reductions to negative human impacts to the carbon cycle.
2. Focus restoration efforts on impaired / degraded open spaces.	2. Reduce human impacts to water quality are buffered by biomass due to vegetative biosynthesis (or fixation) of pollutants -- including, heavy metals.	2. Encourage ecosystems with high diversity tend to be more resistant to human impacts.	2. Increase carbon retained in agricultural systems -- particularly in soil sinks.
3. Establish regional-scale pen spaces as carbon offsets continually every +/- 40 years.	3. Conserve / Restore denitrifying bacteria found in abundance in hydric / mesic systems; reduces impacts to water quality from fertilizer.	3. Conserve / Restore dryland open spaces (particularly degraded sites) as they are easily re-established compared to other open space systems.	3. Improve agricultural yield and resilience through use of carbon additives as fertilizer.
4. Preserve / Restore open spaces to provide future carbon sequestration potential as atmospheric carbon concentrations increase.	4. Reduce sedimentation through natural biomass / physical filters.	4. Slow deforestation and/or forest degradation to preserve dwindling flora and fauna habitat.	4. Transition to nontraditional land management -- longer harvest rotations rather than intensive short-rotation harvests -- significantly improve carbon sequestration efficacy.
5. Establish dryland open spaces as valuable natural open space carbon sinks.	5. Encourage biological uptake and chemical reactions with secondary carbonates to significantly reduce phosphorus pollution.	5. Establish habitat for potential northward shifts of net primary production.	5. Establish plantations -- with lower biodiversity than natural forests -- to reduce pressure on natural forests by serving as sources of forest products.

Figure 34. Design interventions that enhance carbon sequestration benefits in the Lower San Pedro Corridor: climate change mitigation, improved water quality, increased biodiversity, and opportunities for modified agriculture.

Enhancing carbon sequestration in dryland open space systems only offsets a fraction of local human carbon emissions with minimal short-term mitigation of negative impacts to the carbon biogeochemical cycle. Over the long-term (greater than 10,000 years), enhancing carbon sequestration in dryland open space carbon sinks plays a critical roll in transferring carbon from the atmospheric C-pool to stable pedologic C-pools. While there is certainly a strong case for conserving healthy open space systems and restoring degraded drylands, simply as a carbon sink the immediate benefits in regards to climate mitigation are minor and short-lived as vegetation and soils reach a steady state. Enhancing carbon sequestration in drylands open spaces alone will not mitigate negative climate change.

Literature describing the benefits of urban street trees, urban parks, and green roofs often describe significant carbon sequestration benefits. These studies rarely anticipate carbon efflux through vegetative and soil respiration, nor do the studies consider reductions in carbon sequestration efficacy due to removal of biomass and reduced litterfall, poor soils, and the overall life cycle of urban vegetation. While, carbon flux in urban vegetation does result in the short-term sequestering of carbon in aboveground biomass these biomasses are heavily maintained end removed biomass ends up in landfills is burned – releasing sequestered carbon directly into the atmosphere in either case. Furthermore, in dryland urban open spaces water is diverted from local rivers and underground flows resulting in desertification in open spaces – the most efficient carbon sequestration systems. Transfer of carbon from aboveground biomasses to stable secondary carbonates in soils is also impaired. Soils in urban systems are typically poor and easily disturbed, leading to very little long-term carbon sequestration benefits in urban open space systems.

While short-term climate change mitigation benefits are minor due to the scale of human carbon emissions and urban open spaces are not efficient long-term carbon sinks there is tremendous value in enhancing carbon sequestration efficacy in dryland open spaces. Carbon sequestration efficacy is most enhanced in natural open spaces (including large urban parks) where natural processes encourage the formation of secondary carbonates. Immediate benefits of enhancing carbon sequestration efficacy in regional-scale open spaces include: improving water quality, increasing biodiversity, and creating opportunities for sustainable agricultural practices managed to have less impacts to natural processes. Reducing carbon emissions and designing built environments that incorporate natural processes (like carbon sequestration) will lead toward a more balanced existence. Ecologists and designers must continue to collaborate to establish a truly regenerative built environment where ecological processes are anticipated and incorporated into future designs.

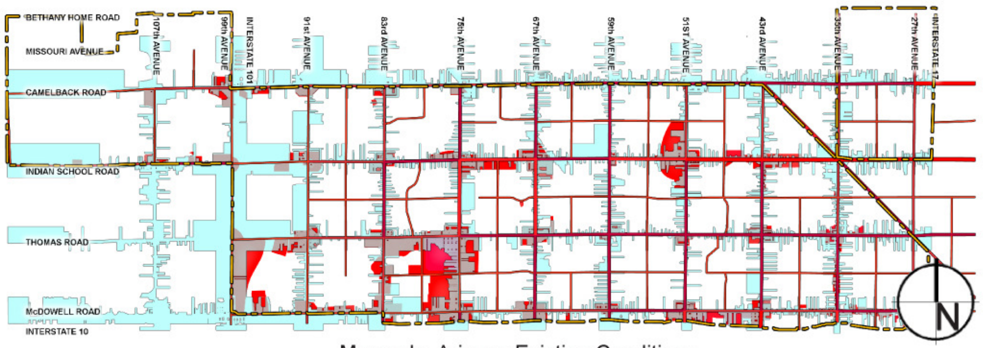
Carbon sequestration is only one part of the equation for addressing overburden of the biogeochemical carbon cycle. Increasing carbon sequestration efficacy carbon sequestration only slows down human impacts to the biogeochemical carbon cycle -- new technologies and design processes are necessary to ensure carbon equilibrium (Lorenz and Lal, 2010). The massive imbalance between human carbon emissions and natural carbon sequestration is exacerbated each time natural open spaces are degraded or destroyed due to negative human impacts and land use. Furthermore, the demonstration portion of this study highlights that increasing carbon sequestration efficacy in open space carbon sinks – even at a regional scale – can not offset the carbon footprints of metropolitan areas. In order for carbon sequestration in natural open spaces to be effective, overall carbon footprints must be substantially reduced primarily through use of alternative, renewable energy – agricultural for energy production, and solar and wind power. Reconciling carbon emissions and sequestration is central to mitigating negative human impacts to the carbon cycle and restoring healthy carbon equilibrium.

Recommendations

“Carbon projects contribute to just one of a hierarchy of actions that can help to combat the effects of climate change” (Great Britain Forestry Commission, 2011, p. 3). Benefits of developing natural carbon sinks include: climate change mitigation, improved water quality, increased biodiversity, and rural business development and diversification. Enhancing carbon sequestration efficacy can be accomplished in a number of ways though developing long-term carbon stocks (i.e. carbon sinks that sequester carbon for over 100 years) provide ongoing environmental, social, and economic benefits including: climate change mitigation, improved water quality, increased biodiversity, and opportunities for enhancing agriculture and establishing farmland soil sinks.

Enhancing and protecting carbon sequestration efficacy in open space systems requires that design emphasis should be placed on conserving and restoring natural open spaces; particularly fragile dryland systems. Restoration and conservancy efforts in dryland open spaces should highlight the importance of re-establishing hydric and mesic as well as existing aridic systems. Minimizing disturbances of existing biomass and biodiversity increase resilience in conserved landscapes. Restoration of degraded open spaces, particularly desertification in dryland open space systems, is also an effective way to enhance carbon sequestration efficacy.

Carbon sequestration can be enhanced in the built environment as well. Re-establishing natural processes in urban open spaces (such as private yards, public parks, right-of-way, medians, streetscapes, and brown fields) may also have significant promise as future carbon sinks. Designers and planners are capitalizing on potential carbon sequestration as a benefit of urban open spaces – some assumptions of carbon sequestration efficacy should be questioned however. When developing carbon sinks designers need to consider long-term residence times of carbon and water embodied in urban biomass; they must question the true increment and benefits of urban biomass (rooftop gardens, street trees, and urban parks) as carbon sinks.



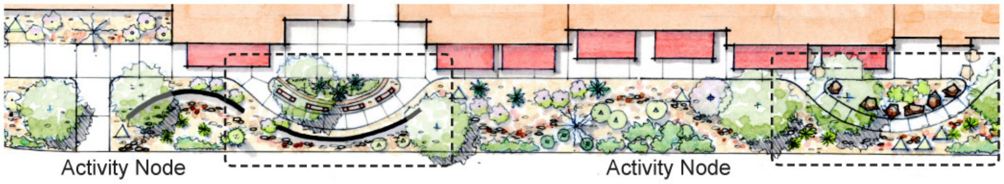
Maryvale, Arizona Existing Conditions

Plan of McDowell Commercial Corridor - Existing

Figure 35. Carbon sequestration efficacy is particularly low in urbanized areas. Maryvale, Arizona is an urbanized area with gridded streets, wide roads, little biomass, and impervious surfaces.

Plan of McDowell Commercial Corridor - Proposed

Section A-A' of McDowell Commercial Corridor - Proposed



Detail Plan of McDowell Commercial Corridor - Proposed

Perspective of Commercial Corridor

<u>Figure 36</u>. Carbon sequestration in commercial corridors can be enhanced by reducing impervious surfaces and promoting natural processes (such as litterfall and soil leaching).

In areas where open space carbon sinks have been replaced with low carbon sequestration efficacy land uses (such as urbanized areas) carbon loss is extremely high. Open spaces in urbanized areas can offer additional benefits including: utilization as activity areas, gathering spaces, modification of microclimate, creation of landmarks, development of place, and many others Designers must also consider the life cycle of carbon embodied in street tree biomass as being particularly short-lived; biomass is removed to landfills where anaerobic decomposition and off-gassing of decaying biomass transfers carbon from the urban vegetative C-pool to the atmosphere as methane and carbon dioxide – methane having an infrared activity 21 times that of carbon dioxide (Scaglia *et al.,* 2010, p. 3). Of critical importance in designing effective carbon sinks in urban open spaces is the re-establishment of natural litterfall and leaching. In areas where urbanization is accruing disturbance of soil carbon C-pools should be minimized by stronger regulation of limits of work and limits of disturbance.

Farmlands efflux nearly all carbon sequestered in farmland soils and biomass during traditional seasonal harvests. Agricultural practices can be modified to implement practices that promote agricultural soil sinks. Establishment of plantation-style farmlands, reduced dependence on monoculture crop rotations, and longer crop rotations help retain carbon sequestered in farmland soils. The use of carbon additives, particularly bio-char and coal fly ash (with heavy metals removed), can provide excellent opportunities to enhance agricultural soils, temporarily increase crop yields, and establish long-term farmland carbon sinks.

This study demonstrates that carbon sequestration efficacy in biotic and pedogenic C-pools can be enhanced through design interventions. However, enhanced efficacy declines as vegetative and soil systems reach a steady state (where carbon influx is nearly equal to carbon efflux in a mature natural open space). Net primary production of biomass (and carbon sequestration efficacy) typically reaches equilibrium in approximately 40 years (though this varies by vegetative system). In order for continued carbon sequestration efficacy to be maintained (along with climate mitigation and other benefits) open space systems must be established continually while critical existing and previously established open spaces must be conserved in order to maintain long-term carbon sequestration in biomass and encourage transfer of carbon to a stable state in soils (a process that can take over 10,000 years). While it is impossible to establish designs that anticipate change over 10,000 years, continual enhancement and establish of open space carbon sinks – in conjunction with massive reductions in human carbon emissions – is critical to restoring balance to the biogeochemical carbon cycle.

Chapter 6

FUTURE RESEARCH

Restoring carbon equilibrium and mitigating negative climate change is possible. Significant research and modeling of natural processes are required followed by implementation of findings by those designing the built environment. Landscape Architects and Planners need to better understand natural cycles -- particularly ecological and biogeochemical processes – in order to incorporate natural processes into our designs and advance a more perfect fusion of the environment, art, and spirit to design that truly inspire regenerative future experiences of Time/Place. Bridging design and ecology is an important ongoing effort; incorporating ecological and design processes are imperative for the development of successful open spaces.

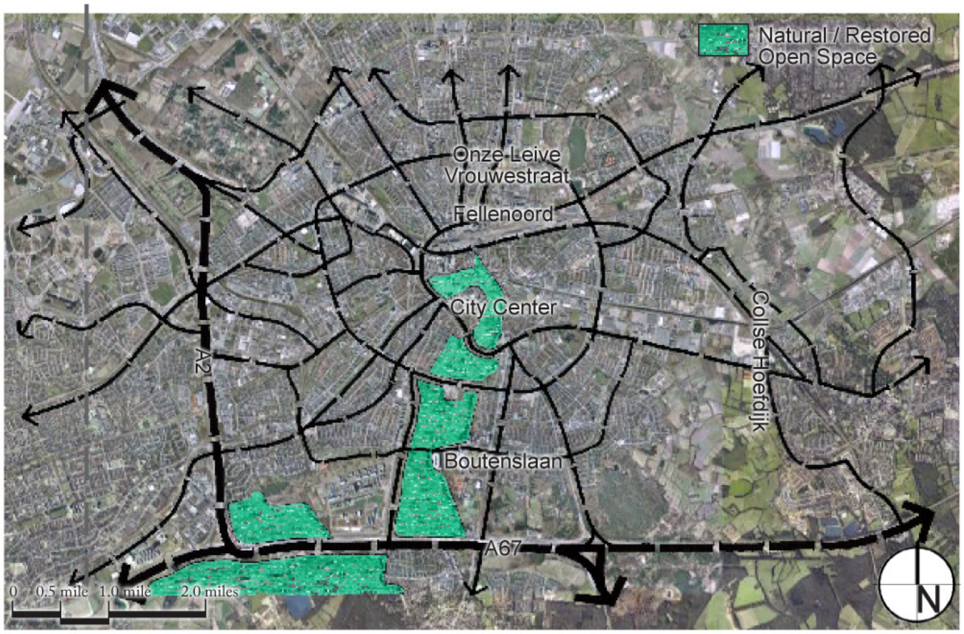


Figure 37. Potential Urban Open Space Carbon Sinks at Eindhoven, NL (metropolitan population: 400,000+) with potential urban open space carbon sink

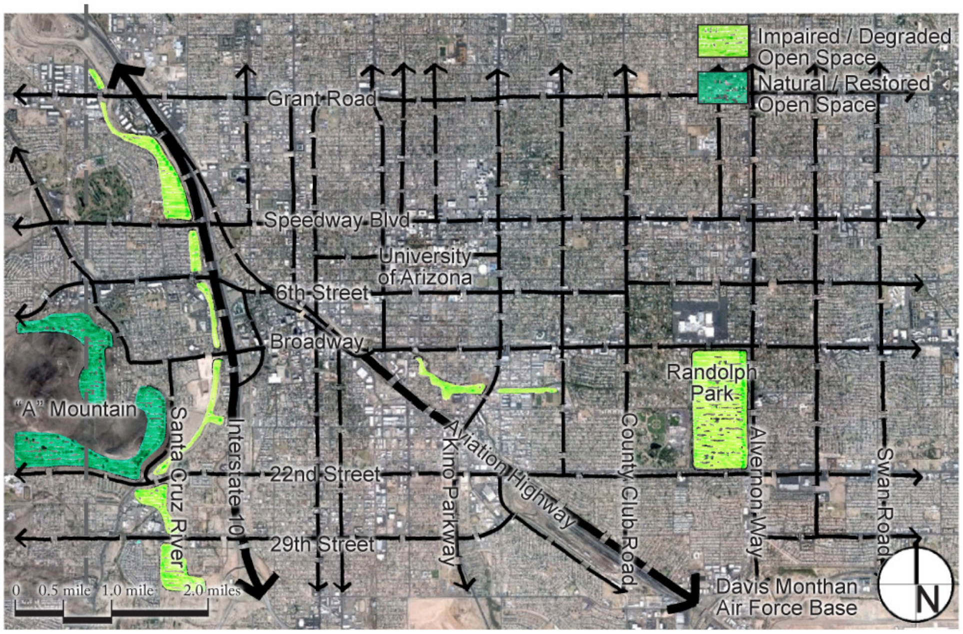


Figure 38. Potential Urban Open Space Carbon Sinks at Tucson, AZ (metropolitan population: 400,000+) showing a tendency for fragmentation of open space in American cities.

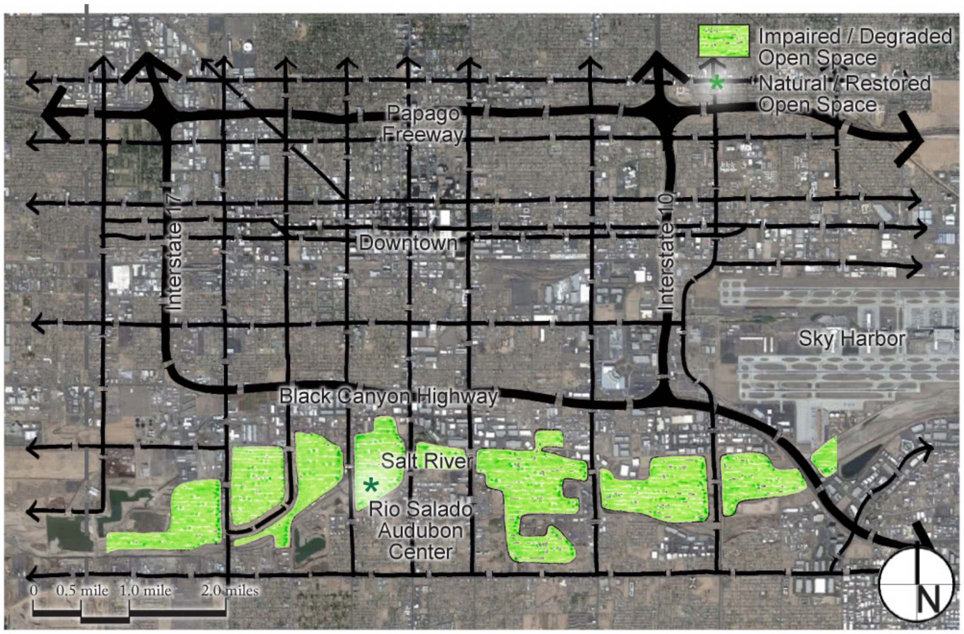


Figure 39. Potential Urban Open Space Carbon Sinks at Phoenix, AZ (metropolitan population: 1,400,000+) highlighting the potential carbon sequestration along the Rio Salado River.

Future research is also required to develop truly regenerative designs. In the context of estimating and analyzing carbon sequestration efficacy, expanding carbon sequestration typologies to include open space systems outside of drylands is imperative. Furthermore, refining carbon sequestration efficacy data – Mg C / ha / y measurements – will increase prediction accuracy of carbon sequestration efficacy in prototype designs. Determination of peak carbon sequestration efficacy in open space systems prior to equilibrium will assist in establishing criteria for establishing natural open space carbon sinks. Further research is needed in determine how mature various open space systems must be to reach a steady state (carbon equilibrium). Establishing carbon-offset projects by in practice will help refine site design, establish precedence for successful design interventions, market natural open space as carbon sinks (added value), and create an educational interface for describing carbon sequestration and derived benefits. Incorporating regenerative open spaces with built environments is also an important first step toward developing a holistic regenerative built environment.

Estimating carbon and communicating value of carbon sequestration is also a promising avenue of research. Developing a global information systems interface for spatially mapping carbon sequestration capacity of existing natural open spaces (and prototype designs) will catalyze and coordinate regional climate change mitigation. Describing the importance of open spaces and specifically enhancing carbon sequestration efficacy in open spaces will help encourage future offset projects. Improving communication between ecology and design is important to continual refinement of design processes as well as an important first step toward future conservancy and enhancement of dryland open space. Advances in mapping the carbon biogeochemical cycle suggest a number of design opportunities for enhancing dryland open space ecological, social, and economic benefits. Conservancy, regulation, and volunteer systems -- such as the United States Green Building Council's Leadership in Energy and Environmental Design (LEED) and the American Society of Landscape Architecture's Sustainable Sites Initiative (SITES) – can ultimately be tailored to protect and reward ongoing efforts to establish a built environment designed in balance with natural processes (USGBC 2011, ASLA 2009). Ecologists and designers must continue to collaborate to establish a truly regenerative built environment where ecological processes are anticipated and incorporated into future designs.

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