Available online at www.sciencedirect.com
ScienceDirect

Urban Forestry & Urban Greening 6 (2007) 49–60

URBAN FORESTRY & URBAN GREENING
www.elsevier.de/ufug

The potential of urban tree plantings to be cost effective in carbon credit markets

Melissa R. McHale[a,*], E. Gregory McPherson[b], Ingrid C. Burke[a]

[a]Graduate Degree Program in Ecology, Department of Forest Rangeland and Watershed Stewardship, Colorado State University, Fort Collins, CO 80523-1472, USA
[b]USDA Forest Service, Pacific Southwest Research Station, Center for Urban Forest Research, Davis, CA 95616 USA

Abstract

Emission trading is considered to be an economically sensitive method for reducing the concentrations of greenhouse gases, particularly carbon dioxide, in the atmosphere. There has been debate about the viability of using urban tree plantings in these markets. The main concern is whether or not urban planting projects can be cost effective options for investors. We compared the cost efficiency of four case studies located in Colorado, and used a model sensitivity analysis to determine what variables most influence cost effectiveness. We believe that some urban tree planting projects in specific locations may be cost effective investments. Our modeling results suggest that carbon assimilation rate, which is mainly a function of growing season length, has the largest influence on cost effectiveness, however resource managers can create more effective projects by minimizing costs, planting large-stature trees, and manipulating a host of other variables that affect energy usage.

Keywords: Carbon credits; Carbon dioxide; Cost effective; Emissions trading; Global climate change; Urban trees

Introduction

Concerns over global climate change have led to an increased interest in reducing atmospheric carbon dioxide (CO_2) concentrations. Advocates for economically sensitive methods for reducing CO_2 emissions have proposed carbon credit trading as an option (Zhang and Folmer, 1995; Ellerman et al., 1998; Petty and Ball, 2001). Carbon credit trading allows industries that cannot feasibly reduce CO_2 emissions to buy credits (each worth one metric ton or tonne, of CO_2) from industries that have reduced their emissions more than the level required. In theory, the market is an economical approach for some industries because it would cost more for them to reduce emissions than to buy credits. Companies can also choose to invest in reforestation projects that remove CO_2 from the atmosphere. In voluntary markets, this is typically called a ‘reduction’ rather than a ‘credit’, but units are still measured in tonnes of CO_2. Similarly, when other greenhouse gases are reduced (methane, nitrous oxide, sulphur hexafluoride, CFCs, and PFCs), ‘carbon equivalents’ can be earned and traded.

The first emissions trading systems were established in 2000 (Petty and Ball, 2001) and on February 16, 2005 the Kyoto Protocol officially took effect, establishing internationally accredited emissions trading. At this time the US has not signed this treaty that requires ratifying nations to reduce greenhouse gas emissions below 1990 levels; however the treaty is endorsed

---

*Corresponding author.
E-mail address: mmchale@lamar.colostate.edu (M.R. McHale).

1618-8667/$ - see front matter © 2007 Elsevier GmbH. All rights reserved.
doi:10.1016/j.ufug.2007.01.001

worldwide, and many US companies with international markets are affected by its implementation.

Community foresters have been considering whether urban tree planting projects can be funded through carbon markets, particularly since carbon trading is now internationally accredited. Tree planting has been considered a method for reducing atmospheric CO_2 because trees sequester CO_2 and store carbon in their biomass through the process of assimilation (Trexler, 1991). Many studies show that urban trees can also reduce atmospheric CO_2 concentrations by affecting energy usage (Rowntree and Nowak, 1991; Nowak, 1993; McPherson, 1998). When trees are close to buildings they directly affect energy usage by shading or blocking wind. Trees indirectly influence energy savings through climate effects; they keep cities cooler in the summer due to shade and transpiration, and warmer in winter by blocking wind (McPherson and Simpson, 2000; Jo and McPherson, 2001).

Although urban trees affect atmospheric CO_2 concentrations in these two ways and it is often assumed that they should be viable for carbon credit trading, there are more requirements involved in trade agreements. Carbon credit projects must be marketable, quantifiable, and cost effective. Investors further require evidence that the atmospheric carbon reduction would not be viable without their support.

The proliferation of tools available to quantify the benefits provided by urban trees is an indication of their marketability. Recent studies have shown that urban trees provide net benefits to communities through reducing atmospheric CO_2 concentration, improving air and water quality, and increasing real estate values, as well as providing many social and psychological benefits for residents (Dwyer et al., 1992; McPherson et al., 1997, 1999, 2003). Because urban trees, especially those on city property, are managed and easily assessed, the carbon assimilated by these trees is inherently quantifiable. Estimating reduced emissions associated with climate-related energy saving is more difficult to measure, but if in question can be considered a supplementary benefit. Also, most community forestry programs are monetarily limited and continually have to compete for funding with other departments within a city, so the associated atmospheric carbon reduction would be directly attributable to assistance provided by investors. Tree maintenance is often a higher priority than planting since the city is accountable for damages associated with lack of tree care, further limiting funding for planting.

The main concern regarding the viability of urban tree planting projects is whether such projects are cost effective investments. Understanding which variables most influence cost effectiveness can assist us in determining, whether management decisions or uncontrollable variables such as climate are playing a larger role in determining a tree planting projects viability in carbon credit markets. It is also important for community foresters to know how they can potentially create more cost effective tree planting projects; even if planting projects do not reach the market, this information is useful for city governments that are voluntarily accounting for total carbon gains and losses, and trying to minimize emissions from the community.

Our goal in this paper is to use a model sensitivity analysis to assess the cost effectiveness of urban tree planting projects. Our key questions are: (1) can urban tree planting projects be cost effective investments? and (2) which variables influence the cost effectiveness of these projects? A host of social factors influence the range of real world values for the variables in the model; therefore, in this study we also aim to compare empirical case studies with potential cost effectiveness quantified in a sensitivity analysis.

Methods

The model

The model "Carbon Dioxide Reduction Through Urban Forestry" (McPherson and Simpson, 2000) consists of a series of calculations that predict (1) total monetary costs, (2) total carbon storage, and (3) reduced energy related carbon emissions over a 40-year period (Fig. 1). These output variables are calculated within the model to determine total cost/tonne of atmospheric CO_2 reduced, and are dependant on input variables for a specific tree planting project. Some input variables are a function of regional factors such as climate, while others are dependant on a local community, or specific decisions by resource managers (Fig. 1). We classified the input variables into these three main categories for the purpose of this analysis, to assess not only which variables affect cost effectiveness, but also which variables may be manipulated in future tree planting projects. Below, we describe the model using these classifications of input variables for the purpose of providing context for our sensitivity analysis; the full model is explained in detail in McPherson and Simpson (2000).

Default values for the input variables

The model was created to help resource managers quantify the cost effectiveness of tree planting projects in their communities (McPherson and Simpson, 2000). Since many of the input variables may be unknown or difficult to determine, default values for these variables are available with the published model; these are suggested by the authors for use when the real values are unknown. The US is divided into 11 representative climate regions based on heating degree days, cooling degree days, latent enthalpy hours, and the ratio of

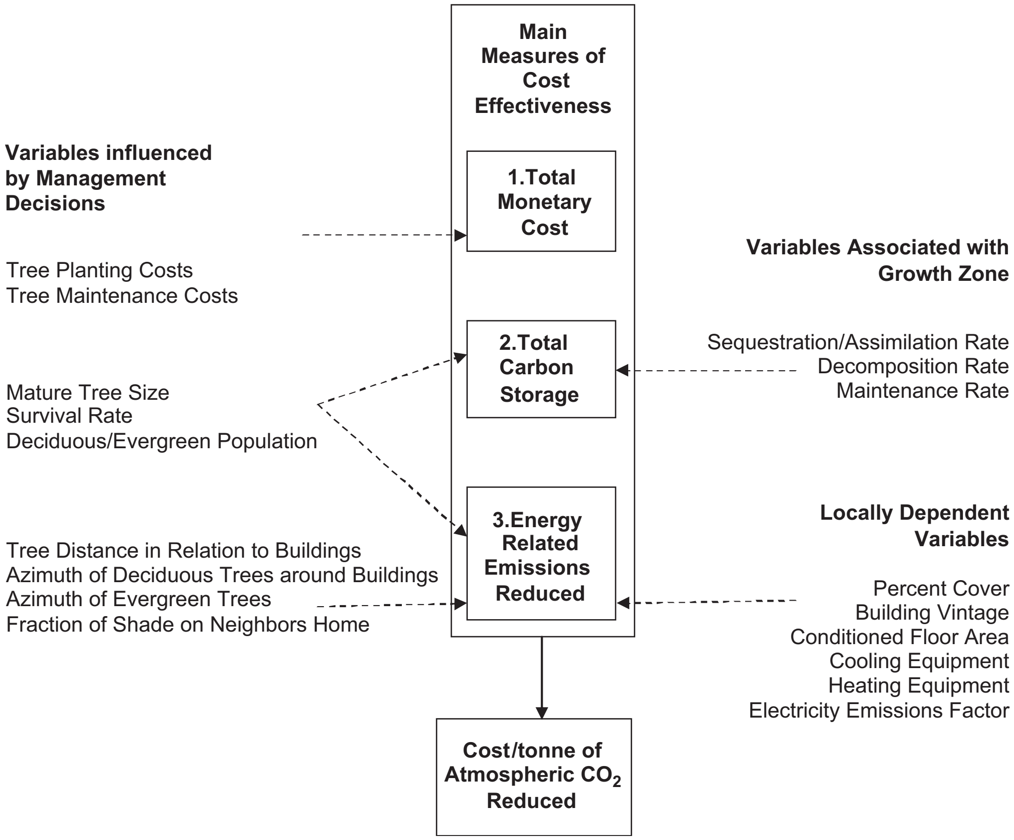

Fig. 1. Input and output variables represented in the model. The model predicts total monetary costs, total carbon storage, and reduced energy-related carbon emissions over a 40-year period. These predictions are based on input variables that are a function of regional processes, characteristics of the local community, or specific management decisions.

average global horizontal radiation to average extra-terrestrial horizontal radiation; default values for all input variables are based on average conditions in each of the 11 climate regions, except for assimilation, decomposition and maintenance rates which are set at a value that is a function of three main tree growth regions.

Input variables influenced by growth region

In this model the US is split into three main growth regions based on mean length of frost free periods: North, Central, and South regions have <180, 180–240, and >240 frost free days, respectively (McPherson and Simpson, 2000). The model includes suggested input values for assimilation, decomposition, and maintenance rates for each of these growth zones. Typically, a user will input default rates assigned to each growth zone because these numbers are a result of complex processes and are difficult to measure, however, different rates can be used. Default assimilation rates for large, medium, and small stature deciduous and evergreen trees were determined by McPherson and Simpson (2000) based on growth curves and biomass equations from the literature with the input of expert reviewers. The southern growth region has the highest assimilation rates per year for all tree types due to a longer growing season (Table 1).

McPherson and Simpson (2000) estimated that all trees removed from urban areas are converted to mulch and decompose rapidly, with up to 80% of the carbon being re-released into the atmosphere within a year. Although this may be a weak assumption, they note that there is little research in this field of urban forestry and based their estimate on research by Melillo et al. (1989) that showed after 4 years 80% of red pine needle litter was gone. Furthermore, the estimates for decomposition rates are likely high, resulting in conservative estimates of the total CO_2 emissions reduced. Decomposition rates are highest in the southern growth zone because decomposition tends to increase with temperature and temperatures remain higher in this region for a longer period of time. Note that here, decomposition rate is considered as a constant input variable based on growth region (Table 1); however, total annual decomposition is also a function of mortality rate and mature tree size. These other input variables are explained in more detail in the section that describes variables influenced by management decisions.

Table 1. Assimilation, decomposition, and maintenance emissions at tree maturity, by growth zone for deciduous (D) and evergreen (E) trees of large, medium, and small stature

Tree type	Assimilation (tonnes/tree/year)			Decomposition (tonnes/tree/year)			Maintenance (tonnes/tree/year)		
	North	Central	South	North	Central	South	North	Central	South
D Large	0.0428	0.1324	0.2937	−0.8754	−2.7107	−6.0188	−0.0051	−0.0078	−0.0106
D Med	0.0262	0.0665	0.1331	−0.5415	−1.3702	−2.7382	−0.0044	−0.0063	−0.0082
D Small	0.0055	0.0153	0.0321	−0.1138	−0.3148	−0.6618	−0.0025	−0.0037	−0.0049
E Large	0.0451	0.1204	0.3028	−0.5807	−2.4449	−6.3920	−0.0047	−0.0084	−0.0121
E Med	0.0073	0.0495	0.1049	−0.1912	−1.0598	−3.1392	−0.0032	−0.0066	−0.0100
E Small	0.0011	0.0126	0.0098	−0.0509	−0.2933	−0.8603	−0.0018	−0.0041	−0.0064

This table was reproduced from McPherson and Simpson (2000).

Maintenance rate is representative of the amount of CO_2 emissions associated with tree care activities. Default maintenance rates for each growth region were determined by a survey of wholesale nurseries, non-profit tree programs and municipal forestry programs (McPherson and Simpson, 2000). Both decomposition and maintenance rates are considered regionally based variables for the purpose of this analysis, however both of these rates can be managed for as well. Decomposition rates supplied in the model may be liberal estimates for advanced urban forestry programs that implement different methods for disposing of dead tree biomass, such as using the material for furniture or other building materials. Maintenance rates are highly variable among various urban forestry programs, however are typically only a small percentage of total carbon emissions (McPherson and Simpson, 2000), but again these estimates could be very different for programs that implement atypical management regimes. Furthermore, separating the US into three tree growth regions is an oversimplification, but allometric equations and detailed research on urban tree growth rates across the country are lacking. Overall this approach, even with some broad simplifications, allowed us to understand the variance in cost effectiveness associated with broad climate regimes and potentially capture the spectrum of tree growth and management in the US.

Locally dependant input variables

Local conditions, like existing tree cover, affect how much more added benefit a local community receives from additional trees. Default existing cover values for reference cities in the model range from 3% to 67%. The age of buildings (pre-1950, 1950–1980, and post-1980) building size (condition floor area ranging from 90.6 to 206.2 m^2), and heating and cooling equipment type (central air conditioning, evaporative cooler, room air conditioning, natural gas, electrical resistance, heat pump, fuel oil, or other heating sources) are all input variables associated with potential energy savings (Fig. 1). Locally dependant input variables are generally dependant on conditions within a community, however some of them may at times also be considered management based variables since managers can choose to plant trees around the least energy efficient buildings in a neighbourhood. The electricity emissions factor is determined by the type of fuel used by the local electricity supplier. For instance, in the model more CO_2 is released per unit of energy from coal than from natural gas. State and regional electricity emissions factors are supplied with the model and range from 0.0722 tonnes CO_2/MWh for Vermont to 1.0456 tonnes CO_2/MWh for North Dakota.

Management-based input variables

Management decisions can directly affect all three output variables associated with cost effectiveness (Fig. 1). Total monetary costs include planting and maintenance costs combined over a 40-year period. These costs are influenced by the type and age of trees planted, how often the trees are watered, pruned, or fertilized, and whether or not volunteers are involved in these processes. Mature tree size (large > 15 m, medium = 10–15 m, small < 10 m) and tree type (evergreen vs. deciduous), directly control the maximum potential carbon storage; larger growing trees contain more biomass and generally half of biomass is carbon (Leith, 1975).

Furthermore, survival rate affects how much of the carbon stored becomes dead tree biomass and is returned to the atmosphere as CO_2 (Table 2). Research has shown that the greatest mortality rates, ranging from 60% to 85%, occur within the first 5 years of establishment (Foster and Blain, 1978; Nowak et al., 1990; Miller and Miller, 1991; Small, 1997). Based on a review of the literature McPherson and Simpson (2000) estimated the number of trees assumed to be alive in 5-year increments (Table 2). In addition to mature tree size, survival rate, and tree type, the placement of trees (azimuth and distance relative to a building) also affects energy-related reductions. In the model, 24 different tree locations relative to buildings affect energy usage: N, NE, E, SE, S, SW, W, NW, at three different distances of 3–6, 6–12, and 12–18 m.

Table 2. Tree survival rates: The percentage of trees planted that are assumed to be alive at the end of each 5-year period

	Tree age intervals in years							
	1–5	6–10	11–15	16–20	21–25	26–30	31–35	36–40
Moderate (%)	75	71	68	64	60	56	53	49
High (%)	85	83	80	78	75	72	70	67
Low (%)	65	60	55	50	45	40	35	30

This table was reproduced from McPherson and Simpson (2000).

Output variables

Input variables are entered into the model, but these values interact within the model for the final calculation of atmospheric CO_2 reduced per total cost. Within the model, total monetary costs are calculated by simply adding the planting and maintenance costs over time; however, calculations for the other output variables, total carbon storage and energy-related emissions, are more complicated (Fig. 1). For instance, the output variable total carbon storage equals the amount of carbon stored in the trees through the process of assimilation, minus the amount of carbon lost through decomposition and maintenance emissions. We input rates of assimilation, decomposition, and maintenance, but the amount of total carbon stored and lost is also a function of mature tree size, survival rates, and whether the trees were deciduous or evergreen (Fig. 1).

Energy-related emissions reduced are associated with local shade and windbreak effects, as well as over climate effects. Only trees that are closer than 18 m are assumed to have a direct effect on building energy usage, while all trees have an impact on the general climate. Energy simulation data included as part of the model were calculated using Micropas 4.01 (Enercomp, 1992) and the shadow pattern simulator (SPS) following methods from Simpson and McPherson (1998) and McPherson et al. (1985).

Sensitivity analysis

We created a representation of the model in an excel spreadsheet and manipulated each input variable independently. Maximum and minimum default values published with the model were input individually into the spreadsheet while all other input variables were held constant (Table 3). In this part of the analysis, total monetary cost was held constant; therefore cost effectiveness is solely a function of the amount of atmospheric CO_2 reduced.

Case study analyses

We analysed the cost effectiveness of four proposed tree planting projects in Colorado. In the model, Colorado is a part of the northern growth zone, and due to the short growing season, we expected this to be one of the least cost effective areas. The reference city for the supplied default values in the Rocky Mountain region was Denver, which was the first of our case studies (Table 4). In a second case study we evaluated an actual tree planting project in a small Denver neighbourhood, called Whittier. In the other two case studies, we evaluated proposed tree planting projects in Fort Collins and Grand Junction. The Fort Collins planting consisted entirely of street trees that were in close proximity to neighbouring houses, and the planting project in Grand Junction was planned for the surrounding park system. These case studies were representative of a range of potential urban tree planting projects in Colorado. In instances where variables were unknown for an area the default values for Denver were used (Table 4).

Results and discussion

The sensitivity analysis

Assimilation rate, a variable controlled by regional growth zone, had the most influence on a project's cost effectiveness (Fig. 2). Essentially, areas with a longer growing season (>240 days) demonstrated a greater chance to develop cost effective projects. The assimilation rates used in this model were generalized and for this reason tree growth and biomass should be more accurately quantified over time in future established carbon credit projects.

A locally dependant variable, existing tree cover, was next most important (Fig. 2). The effects on microclimate and energy usage of additional tree cover diminished as the percent of existing cover increased. The effects of tree cover exceeded those of other variables by 100% or more, but it was only important in planting projects where energy savings were quantified. Although when tree cover is high it could have an affect on assimilation rate due to increased tree competition for light and other resources, this model did not take those effects into account.

Mature tree size was the third most important variable influencing cost effectiveness; larger-stature trees stored more carbon and had a greater effect on

Table 3. Input variables for the model

Variable	Description	Dependence	Sequestration or energy effects	Max. values	Min. values
Assimilation/ sequestration	The rate trees assimilate carbon, which is dependant on growth rate.	Growth zone	Sequestration	Rates associated with the southern growth zone (Table 2)	Rates associated with the northern growth zone (Table 2)
Decomposition	Expected decomposition rate of trees that do not survive.	Growth zone	Sequestration	Rates associated with the southern growth zone (Table 2)	Rates associated with the northern growth zone (Table 2)
Maintenance	Amount of projected maintenance emissions.	Growth zone	Sequestration	Rates associated with the southern growth zone (Table 2)	Rates associated with the northern growth zone (Table 2)
Percent cover	The percent of building and tree cover already existing in the community.	Local area	Energy	100%	0%
Building vintage	The age of local buildings.	Local area	Energy	All houses are built Pre-1950	All houses are built post-1980
Conditioned floor area	The size of local homes.	Local area	Energy	206.2 m	90.6 m
Cooling equipment adjustment	The type of equipment used to keep buildings cool.	Local area	Energy	All houses have central air	No houses have air conditioning
Heating equipment Adjustment	The type of equipment used to heat local buildings.	Local area	Energy	All houses use electrical resistance	All houses use natural gas
Electricity emissions factor	Carbon dioxide emissions associated with the local electricity supplier	Local area	Energy	1.0456 tonnes of CO_2/MWh	0.0722 tonnes of CO_2/MWh
Mature tree size	How large the planted trees are expected to grow at maturity.	Direct management decisions	Both	All large stature trees	All small stature trees
Survival	Expected rate of survival of the trees planted.	Direct management decisions	Both	Maximum survival rate (Table 3)	Minimum survival rate (Table 3)
Near/far	How close a tree is to buildings.	Direct management decisions	Energy	All trees are near homes (closer than 15 m)	All trees are far from homes (further than 15 m)
Shade effects	Azimuth of deciduous trees serving to shade buildings in the summer.	Direct management decisions	Energy	Trees are distributed N, NE, NW, W	Trees are distributed E, SE, S, SW
Deciduous/ evergreen	Number of trees that do or do not lose their leaves in winter.	Direct management decisions	Both	All trees are deciduous	All trees are evergreen
Wind effects	Azimuth of evergreen trees serving as windbreaks for local buildings.	Direct management decisions	Energy	N, NE, NW, W	E, SE, S, SW
Shade fraction	The fraction of shade a tree will provide a neighbouring home.	Direct management decisions	Energy	100%	0%

The main model input variables are dependant on regional processes associated with growth zones, characteristics of local communities, or are affected by direct management decisions. The variables can have sequestration effects (direct assimilation effects) or effects on energy-related emissions. Minimum and maximum values for each variable were used in the sensitivity analysis to determine which variables had the greatest influence on cost-effectiveness.

Table 4. Input variables associated with the four Colorado case studies

	Denver	Whittier	Grand junction	Fort Collins
Assimilation/ sequestration	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)
Decomposition	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)
Maintenance	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)	Northern Growth Zone (Table 2)
Percent cover	56	46	56	56
Building vintage	Pre-50: 42% 50–80: 48% Post-80: 10%	Pre-50: 80% 50–80: 20% Post-80: 0%	Pre-50: 42% 50–80: 48% Post-80: 10%	Pre-50: 42% 50–80: 48% Post-80: 10%
Conditioned floor area	Pre-50: 90.6 m 50–80: 100.3 m Post-80: 192.3 m	Pre-50: 180.7 m 50–80: 194.5 m Post-80: N/A	Pre-50: 90.6 m 50–80: 100.3 m Post-80: 192.3 m	Pre-50: 90.6 m 50–80: 100.3 m Post-80: 192.3 m
Cooling equipment	Table 6	No cooling: 40% Room air: 40% Evap. cooler: 5% Central air: 5%	Table 6	Table 6
Heating equipment	Table 6	Natural gas: 90% Other: 10%	Table 6	Table 6
Electricity emissions factor	0.908 tonnes of CO_2/MWh	0.86184 tonnes of CO_2/MWh	0.908 tonnes of CO_2/MWh	1.002 tonnes of CO_2/MWh
Mature tree size	Large: 49.5% Med: 36.5% Small: 14%	Large: 80% Med: 15% Small: 5%	Large: 75% Med: 0% Small: 25%	Large: 64% Med: 22% Small: 14%
Survival	Moderate (Table 3)	Moderate (Table 3)	Moderate (Table 3)	Moderate (Table 3)
Near/far	Near = 50% Far = 50%	Near = 100% Far = 0%	Near = 0% Far = 100%	Near = 69% Far = 31%
Shade effects	N = 4%, NE = 14%,E = 29%,W = 34%, NW = 19% E = 14%,SE = 8%, S = 14%, SW = 8%, W = 12%, NW = 10%	N = 24%, E = 44%, S = 11%, W = 21%	Not applicable	N = 21%, NE = 13%,
Deciduous/ evergreen	Dec: 90% Evr: 10%	Dec: 100% Evr: 0%	Dec: 75% Evr: 25%	Dec: 100% Evr: 0%
Wind effects	N = 4%, NE = 14%, E = 29%, W = 34%, NW = 19%	Not applicable	Not applicable	Not applicable
Shade fraction	15%	15%	15%	15%

the surrounding microclimate than smaller trees. Studies show that large growing trees actually provide more storm water runoff reduction and air quality benefits to a community than small trees (Dwyer et al., 1992; McPherson et al., 1997, 1999, 2003) so favoring large trees is a positive management strategy, assuming space and resources are available.

The equipment used to keep homes cool in the summer, building age, carbon dioxide emissions associated with the electricity supplier, and building size were moderately important variables in the model and all were dependant on the locality of the tree planting project (Fig. 2). These variables also influenced energy usage; larger homes, older homes, and homes that have

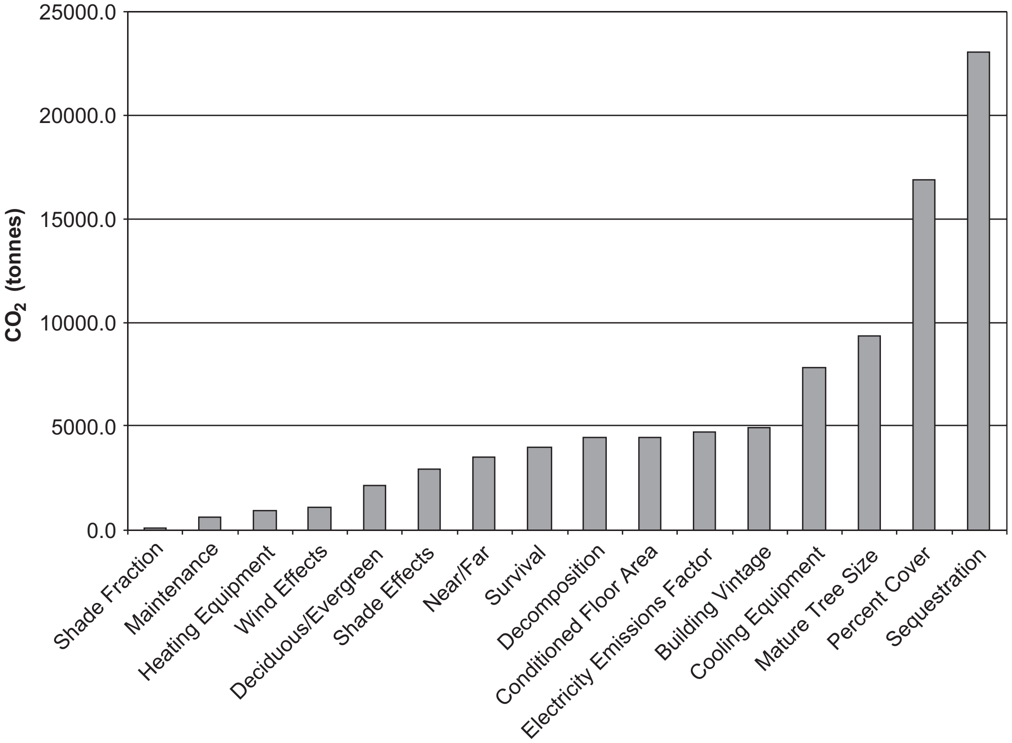

Fig. 2. Sensitivity analysis results show the change in CO_2 (tonnes) associated with minimum and maximum values for each input variable. The values for each input variable are shown in Table 1. Assimilation rate (sequestration) and the amount of existing cover (percent cover) were the two variables that had the greatest affect on cost-effectiveness in the model "Carbon Dioxide Reduction Through Urban Forestry".

central air conditioning required the most energy to keep cool in the summer. Therefore trees shading these types of buildings had an increased effect on energy usage. Also, if we modelled the situation such that the local electricity supplier used coal as a fuel source, there was more carbon emitted per unit energy used than if a cleaner source such as wind was available. This means that more carbon will be reduced from future plantings in areas that use less efficient energy sources. However, it is important to note an effective strategy for offsetting fossil fuel emissions could be using trees planted as part of carbon credit projects as an energy source.

Decomposition rate, another variable influenced by growth zone, was a moderately influential variable. It is important to note that the rates used were liberal resulting in conservative estimates of atmospheric CO_2 reduced. The underlying assumption was that 80% of all dead tree biomass was immediately released into the atmosphere through decomposition. Although decomposition rate was a function of growth zone in the model, future planting projects designed for carbon credit markets can manipulate this high rate of decomposition by dedicating removed trees to other more slowly decomposing resources such as furniture.

Survival rate, distance and azimuth of trees relative to buildings, and tree type had smaller impacts on cost effectiveness, but if managed for in future projects, these variables together could potentially influence cost effectiveness. Maintaining the highest survival rates and strategically planting trees where they have more influence on energy usage can make a project more effective. In this analysis we used expected survival rates based on a review of the literature (McPherson and Simpson, 2000); however it is possible that with extra care survival rates could exceed the range of values used here and this would increase the potential impact of this variable. Trees planted closer than 15 m directly affected building energy usage, but if they were located E, SE, S, or SW relative to a building there were more negative energy effects in winter. This point is particularly important for communities with a short growing season, where the negative winter effects will be quantified over a longer period of time. Trees located farther than 15 m still affected energy usage by changing the local microclimate, and these effects were generally positive.

Trees did not have the same effect on energy consumption in the winter as in the summer, therefore effects of evergreen trees serving as windbreaks and the type of equipment used to heat homes provided less energy-related benefits than shade trees in the summer or the cooling equipment in homes (Fig. 2). According to the model, maintenance emissions were a function of growth zone and had little impact on cost effectiveness, however studies have shown that over time maintenance emissions can significantly reduce the CO_2 mitigation potential of urban forests (Nowak et al., 2002). The fraction of shade a tree provided for neighbouring homes hardly impacted the results at all, and may be overlooked in future analyses.

Case study analyses

In these analyses we modified all input variables, including monetary costs. Of the four case studies in Colorado, the Denver study, consisting entirely of model supplied values, was the most cost effective ($145/tonne) (Tables 5 and 6). Cost effectiveness was directly related to planting and maintenance costs over a 40-year period, and reported on a per tree basis, Denver had the lowest costs ($100/tree as opposed to $116, $200, and $570 per tree for Whittier, Grand Junction and Fort Collins, respectively). Costs associated with the Denver analysis were based on the default values supplied with the model, and although they were lower than costs for other case studies these costs were also attainable, especially if small seedling trees were planted as opposed to trees larger in caliper (>4 cm). Fort Collins was the least cost effective case study and also had very high planting and maintenance costs. The estimated costs were higher in Fort Collins for a few reasons. First, the city's planting spaces were in the right of way (ROW) where only large caliper trees, that cost more, survive well. Second, the city pays staff to plant trees, as opposed to Whittier, which included volunteers to reduce costs. Third, we estimated high maintenance costs for Fort Collins because of the intensive management practices associated with the safety and appearance of street trees.

When we analysed the case studies according to the amount of carbon stored or CO_2 emissions saved on the per tree basis, the Fort Collins tree planting would actually contribute the most at the end of a 40-year period (0.9 tonnes of CO_2/tree), however, all the case studies were very similar; 0.6, 0.7, and 0.8 tonnes of CO_2 per tree for Whittier, Denver, and Grand Junction. The small difference was attributable to energy-related effects; when we removed these effects, and only accounted for tree growth, maintenance, and death and decomposition, all four case studies had a net assimilation rate equal to 0.3 or 0.4 tonnes of CO_2 per tree over a 40-year period.

Trees can have both direct and indirect effects on energy savings. The balance between the direct (shade) and indirect (climate) energy effects determined the overall contribution of energy effects to each study (Fig. 3). The direct effects were not necessarily a positive contribution to net carbon saved by tree planting

Table 6. Percentage of homes in each building vintage with different heating and cooling types

	Vintage of housing		
	Pre-1950 (%)	1950–1980 (%)	Post-1980 (%)
Cooling equipment			
Central air conditioning	38	56	72
Evaporative cooling	0	0	0
Room air conditioning	37	23	25
No cooling	26	21	3
Heating equipment			
Natural gas	69	61	50
Fuel oil	18	19	0
Electrical resistance	2	10	21
Heat pump	0	2	4
Other heating	10	8	25

This table was reproduced from McPherson and Simpson (2000).

Table 5. Cost effectiveness of the four Colorado case studies with and without energy effects[a]

	Trees planted	Total cost ($)	Net CO_2 saved (metric tonnes) (w/energy effects)	Cost/tonne (w/energy effects) ($)	Net CO_2 saved (metic tonnes) (w/o energy effects)	Cost/tonne (w/o energy effects) ($)
Denver	10,000	100,000	6890	145.10	2883.6	346.79
Whittier	232	27,100	134.5	201.50	84.9	319.20
Grand junction	460	92,000	362.6	253.70	150.3	612.11
Fort Collins	1415	807,000	1246.8	647.26	632.1	1276.70

[a] Denver and Whittier analyses did not include long-term maintenance costs. The Grand Junction costs were an estimate of planting large caliper trees in parks, with a minimal amount of maintenance costs associated with short-term watering. Fort Collins predicted significant maintenance costs associated with old and large street trees throughout 40 years of growth. The costs for these projects were only estimates, except for Whittier where we analysed the project after it was completed.

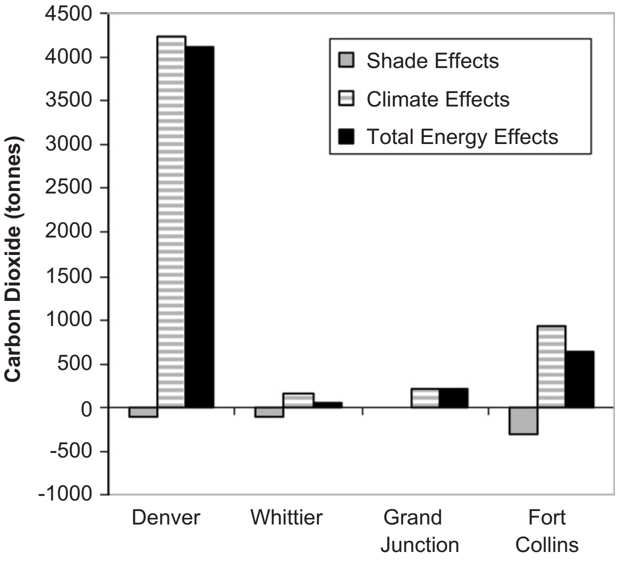

Fig. 3. Direct (shade) and indirect (climate) effects determine total energy effects. Direct (shade) effects were not a positive contribution to net carbon saved in Denver, Whittier, and Fort Collins.

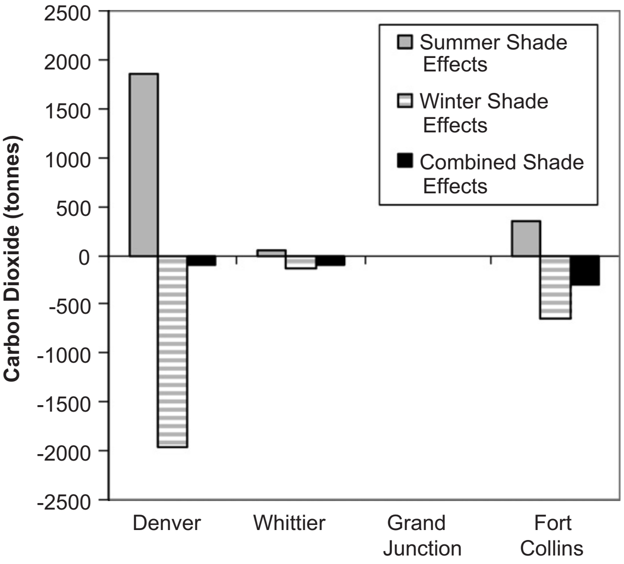

Fig. 4. Combined direct (shade) energy effects were a function of shading in both winter and summer. In most case studies the negative effects of shade in winter outweighed the positive summer shade effects.

projects in Colorado. Where summers are short and winters are long, trees can increase heating costs more than they decrease cooling costs. In all of the case studies this was the tendency, except in Grand Junction where direct shading effects were non-existent because trees were located too far from buildings (Figs. 3 and 4). In the Denver analysis, direct shading effects were not as negative as the other studies because trees around buildings were in more ideal locations (Fig. 3) and the positive effects associated with shading in the summer outweighed the negative winter effects (Fig. 4).

Climate effects were high in the Denver case study (Fig. 3), which was mostly a function of the large number of trees associated with this study. On the per-tree basis, all of the case studies had greater climate effects than the Denver study (0.66 tonnes CO_2/tree for Fort Collins and Whittier, 0.47 tonnes CO_2/tree for Grand Junction and 0.42 tonnes CO_2/tree for Denver). Climate effects were influenced by the percent cover of buildings and trees existing in an area as well as the mature size of the trees planted. A high percentage of trees in both the Fort Collins and Grand Junction plantings were large because Fort Collins is not limited by overhead wires or small planting spaces, and in Grand Junction the plantings were planned for parks.

The case-studies in today's carbon credit market

None of the Colorado case studies were cost effective enough to compete in today's carbon credit markets. At this time, rates in active markets range from \$3 to \$13 (www.CO2e.com) and all of these studies significantly exceeded that range in costs by \$100 or more (Table 5). Furthermore, if energy effects were not accounted for, cost efficiency decreased (Table 5).

However, a more in depth analysis of the Denver case study shows that it is not impossible for an urban tree planting project to be cost effective and perhaps even a competitive program according to today's market standards. If the Denver case study had the assimilation rate associated with the southern growth zone then the cost/tonne CO_2 was reduced to \$33. On the other hand, if the Denver study consisted of only small trees, the cost/tonne CO_2 would increase to \$1051. This huge variation created by simply changing one variable in this analysis verified that the cost effectiveness of urban tree planting projects is highly dependant on location and management decisions. Although \$33 a credit is still higher than average rates in markets today, this lower rate was achieved by changing only one variable; if the Denver study was in the southern growth zone and consisted of all large trees then the cost decreased even more to \$23/tonne. Furthermore, buyers in voluntary markets have been paying relatively higher prices for credits and are willing to pay more for credits associated with highly sustainable, socially beneficial projects (www.CO2e.com).

Highly variable costs have also been found for rural-based carbon offset projects. The estimated costs per tonne of CO_2 sequestered for converting agricultural land to forests throughout the eastern US has been found to range from \$10-\$400 per tonne (Brown et al., 2005; Walker et al., in press). The variability is dependant on the length of afforestation, the costs associated with planting and project development, and most significantly opportunity costs, or the earning potential lost from the conversion of land from agriculture to forest. Most of the urban case studies in this analysis also fall within that range, which shows that urban projects have competitive potential with other carbon offset projects.

Conclusion

There are several key decisions that forest managers can make to influence cost effectiveness. Although community forests are potentially acceptable and marketable solutions to storing CO_2, only very few, specifically designed urban tree planting projects would be cost effective at this time. Our modelling results suggest that projects in the southern growth zone and/or projects that include energy-related carbon benefits are more likely to be cost effective according to today's markets. As markets become established, credit prices are expected to increase, and foresters will have a better chance of fully funding tree planting projects in communities, as well as being able to monetarily manage those forests until maturity. Moreover, it is important to consider that there are other benefits associated with urban trees, and because of these added benefits, investors may be willing to spend more per credit than they would for other projects dedicated to only reducing atmospheric CO_2 concentrations.

Acknowledgements

Funding for this project was provided by the Colorado State Forest Service and the USDA Forest Service. We are indebted to Ralph Campbell and the Colorado Tree Coalition for the passionate interest and support that stimulated this research. Michael Swanson, Tim Buchanan, Ralph Zentz and Vince Urbina provided valuable information and guidance on urban tree management specifications as well as typical community characteristics. We thank Kirsten Romig for collecting and organizing our field data. Sonia Hall and John Bradford provided critical feedback on this research and manuscript. Sarah Walker and Sandra Brown shared information on their new research on costs effectiveness of rural carbon offset projects which was a great addition to the interpretation of this analysis. We would also like to thankfully acknowledge two unknown reviewers and the editors of Urban Forestry and Urban Greening for positive feedback that significantly improved this manuscript.

References

Brown, S., Kadyszewski, J., Walker, S., Grimland, S., 2005. Carbon supply from sequestration activities on agriculture and forest lands for the SECARB Partnership. US DOE, Southeast Regional Carbon Sequestration Partnership.

Dwyer, J.F., McPherson, E.G., Schroeder, H.W., Rowntree, R.A., 1992. Assessing the benefits and costs or the urban forest. Journal of Arboriculture 18 (5), 227–234.

Ellerman, D.A., Jacoby, H.D., Decaux, A.D., 1998. The effects on developing countries of the Kyoto Protocol and carbon dioxide emissions trading. World Bank Policy Research Working Paper 2019, Washington, DC.

Foster, R., Blain, J., 1978. Urban tree survival; trees in the sidewalk. Journal of Arboriculture 4, 14–17.

Jo, H.-K., McPherson, E.G., 2001. Indirect carbon reduction by residential vegetation and planting strategies in Chicago, USA. Journal of Environmental Management 61, 165–177.

Leith, H., 1975. Modeling the primary productivity of the world. Ecological Studies 14, 237–263.

McPherson, E.G., 1998. Atmospheric carbon dioxide reduction by Sacramento's urban forest. Journal of Arboriculture 24 (4), 215–223.

McPherson, E.G., Simpson, J.R., 2000. Carbon dioxide reductions through urban forestry: guidelines for professional and volunteer tree planters. PSW GTR-171, USDA Forest Service, Pacific Southwest Research Station, Center for Urban Forest Research, Albany, CA.

McPherson, E.G., Brown, R., Rowntree, R.A., 1985. Simulating tree shadow patterns for building energy analysis. In: Wilson, A.T., Glennie, W. (Eds.), Solar 85: Proceedings of the National Passive Solar Conference. American Solar Energy Society, Boulder, CO, pp. 378–382.

McPherson, E.G., Nowak, D., Heisler, G., Grimmond, S., Souch, C., Grant, R., Rowntree, R.A., 1997. Quantifying urban forest structure, function, and value: the Chicago urban forest climate project. Urban Ecosystems 1, 49–61.

McPherson, E.G., Simpson, J.R., Peper, P.J., Xiao, Q., 1999. Benefits and costs of Modesto's municipal urban forest. Journal of Arboriculture 25 (5), 235–248.

McPherson, E.G., Simpson, J.R., Xiao, Q., Peper, P.J., Maco, S.E., 2003. Benefit-cost analysis of Fort Collins' Municipal Forest. Internal Report. CUFR-2, USDA Forest Service, Pacific Southwest Research Station, Center for Urban Forest Research 2, Albany, CA, pp. 1–39.

Melillo, J.M., Aber, J.D., Linkins, A.E., Ricca, A., Fry, B., Nadelhoffer, K.J., 1989. Carbon and nitrogen dynamics along a decay continuum: plant litter to soil organic matter. Plant and Soil 115, 189–198.

Miller, R.H., Miller, R.W., 1991. Planting and survival of selected tree taxa. Journal of Arboriculture 17 (7), 185–191.

Nowak, D.J., 1993. Atmospheric carbon reduction by urban trees. Journal of Environmental Management 37 (3), 207–217.

Nowak, D.J., McBride, J., Beatty, R.A., 1990. Newly planted tree growth and mortality. Journal of Arboriculture 16 (5), 124–129.

Nowak, D.J., Stevens, J.C., Sisinni, S.M., Luley, C.J., 2002. Effects of urban tree management and species selection on atmospheric carbon dioxide. Journal of Arboriculture 28 (3), 113–122.

Petty, J., Ball, A., 2001. Agricultural influences on carbon emissions and sequestration: a review of evidence and the emerging trading options. Center for Environment and Society Occasional Paper 10001-03, University of Essex, Colchester.

Rowntree, R.A., Nowak, D.J., 1991. Quantifying the role of urban forests in removing atmospheric carbon dioxide. Journal of Arboriculture 17 (10), 269–275.

Small, B.M., 1997. Tree Growth under Sacramento Shade. Sacramento Tree Foundation, Sacramento, CA.

Trexler, M.C., 1991. Minding the carbon store: weighing US forestry strategies to slow global warming, World Resources Institute, New York, NY.

Walker, S., Grimland, S., Winsten, J., Brown, S., in press. Part IIIA opportunities for improving carbon storage through afforestation of agricultural lands. In: Terrestrial Carbon Sequestration in the Northeast Quantities and Costs. US DOE-NETL, Pittsburgh, PA.

Zhang, Z., Folmer, H., 1995. The choice of policy instruments for the control of carbon dioxide emissions. Intereconomics 30 (3), 133–142.