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Indirect carbon reduction by residential vegetation and planting strategies in Chicago, USA

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Concern about climate change has evoked interest in the potential for urban vegetation to help reduce the levels of atmospheric carbon. This study applied computer simulations to try to quantify the modifying effects of existing vegetation on the indirect reduction of atmospheric carbon for two residential neighborhoods in north-west Chicago. The effects of shading, evapotranspiration, and windspeed reduction were considered and were found to have decreased carbon emissions by 3·2 to 3·9% per year for building types in study block 1 where tree cover was 33%, and −0·2 to 3·8% in block 2 where tree cover was 11%. This resulted in a total annual reduction of carbon emission averaging 158·7 (±12·8) kg per residence in block 1 and 18·1 (±5·4) kg per residence in block 2. Windspeed reduction greatly contributed to the decrease of carbon emission. However, shading increased annual carbon emission from the combined change in heating and cooling energy use due to many trees in the wrong locations, which increase heating energy use during the winter. The increase of carbon emission from shading is somewhat specific to Chicago, due in part to the large amount of clean, nuclear-generated cooling energy and the long heating season. In Chicago, heating energy is required for about eight months from October to May and cooling energy is used for the remaining 4 months from June to September. If fossil fuels had been the primary source for cooling energy and the heating season had been shorter, the shading effects on the reduction of carbon emission would be greater. Planting of large trees close to the west wall of buildings, dense planting on the north, and avoidance of planting on the south are recommended to maximize indirect carbon reduction by residential vegetation, in Chicago and other mid and high-latitude cities with long heating seasons.

Keywords: climate change, carbon dioxide, urban vegetation, building energy savings, proper planting.

Introduction

Carbon dioxide plays the major role absorbing outgoing terrestrial radiation and contributes about half of the total greenhouse effect (Ciborowski, 1989; Rodhe, 1990). The atmospheric CO_2 concentration is currently rising by 4% per decade due to fossil fuel combustion and deforestation (Ciborowski, 1989; Post *et al*., 1990). Existing studies (Hansen *et al*., 1988; Washington and Meehl, 1989; Mitchell *et al*., 1990) predict that this continued trend in CO_2 emissions could result in a doubling of preindustrial CO_2 concentrations and climate change within the next 50 to 100 years. If the existing projection is correct, such changes may pose a serious threat to ecological and socio-economic systems (Pastor and Post, 1988; Smith and Tirpak, 1988; Melillo *et al*., 1990; Schlesinger, 1991).

Concern about the greenhouse effect has evoked interest in the potential for urban vegetation to help reduce the level of atmospheric CO_2. Urban vegetation reduces cooling energy use and decreases carbon emissions by blocking solar radiation reaching building structures, and by creating cool microclimates near buildings through evapotranspiration. Huang *et al*. (1992) estimated that a 10% increase in tree cover can save annual cooling energy by 24% in Sacramento, CA and 12% in Phoenix, AZ. Most of the cooling energy savings are attributed to the effect of evapotranspiration and only 10 to 30% to shading (Huang *et al*., 1987, 1992). Urban

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trees scattered throughout a neighborhood also reduce heating energy use by increasing surface roughness and by reducing windspeeds. Lower windspeed decreases infiltration of cold outside air into the interior of buildings, which is largely responsible for heat loss in winter. Huang *et al.* (1990) found that reduced infiltration from wind shielding by three trees around a well-insulated residence can save heating energy by 16% in Chicago. Therefore, urban vegetation can be adopted as one measure to reduce carbon emissions associated with energy use. Some researchers (Akbari *et al.*, 1988; Beatty, 1989; Parker, 1989) emphasized the necessity of systematic planting guidelines to decrease energy use and carbon emissions in urban areas.

However, information is limited about urban vegetation impacts on energy and carbon fluxes. Regional variations in climate and the mix of fuels used to generate energy influence the potential reduction of carbon emissions. In Chicago, 83·5% of cooling energy was produced from nuclear power and the remaining 16·5%, from fossil fuels. Appropriate planting strategies around residential buildings are critical, especially, in mid and high-latitude regions because tree shade on south-facing surfaces could increase heating energy use in winter (Minnesota Department of Natural Resources, 1991; McPherson *et al.*, 1993b). The first objective of this study was to quantify shading, evapotranspiration, and wind-reduction effects of existing vegetation on the indirect reduction of atmospheric carbon for residential neighborhoods in Chicago. The second objective was to determine effective planting strategies to reduce energy consumption and carbon emissions. In this study, the indirect reduction of atmospheric carbon indicates carbon emissions avoided at power plants from savings of cooling and heating energy.

Study area and methods

Study area

Two residential blocks located in northwest Chicago were selected as the study area. The two blocks were chosen to reflect difference in energy consumption associated with difference in vegetative cover. Block 1 is enclosed by W. Catalpa Ave. and W. Rascher Ave., and N. Virginia Ave. and N. Francisco Ave. Block 2 is enclosed by W. Bryn Mawr Ave. and W. Gregory St., and N. California Ave. and N. Washtenaw Ave. The two blocks are separated by about 240 m. Blocks 1 and 2 have 22 and 28 residential units, and are 1·9 and 1·6 ha in size, respectively. In block 2, one large multi-family residential unit was excluded because it was untypical of building types and sizes in the study area.

Climate

The climate of Chicago is a moist mid-continental type with considerable seasonal variation in precipitation and temperature. Annual temperature averaged about 9·4°C, and annual precipitation averaged about 905 mm during 30 years from 1963 to 1992 (NOAA, 1993). Mean monthly temperatures ranged from −5·8°C in January to 22·9°C in July. Precipitation was at a maximum in August with 106 mm and at a minimum in February with 35 mm. Average windspeed was 4·6 m/s, and windiest period was January through April (NOAA, 1993). Heating energy is required for about eight months from October to May and cooling energy is used for the remaining 4 months from June to September.

Trees

The most common tree species in the study area were maples (*Acer negundo*, *A. platanoides* and *A. saccharinum*), elms (*Ulmus americana* and *U. pumila*), mulberry (*Morus alba*), crabapple (*Malus* spp.), cherry (*Prunus* spp.), and spruces (*Picea abies*, *P. glauca* and *P. pungens*). Analysis of the dbh (trunk diameter at breast height) distribution of trees revealed that the tree population in the study area was relatively small. Trees with a dbh less than 20 cm accounted for 75%. Tree cover averaged about 33% per residential unit in block 1 and 11% in block 2. Tree cover in Chicago was about 15% for one- to three-family residential lands (McPherson *et al.*, 1993a). Therefore, block 2 is more characteristic of average city conditions in residential lands.

Lot area and land-cover types

Total lot area ranged from about 583 m^2 to 2428 m^2 (mean = 978·9 m^2) in block 1, and from about 308 m^2 to 1146 m^2 (mean = 503·1 m^2) in block 2. The mean lot area was about two times larger in block 1 than in block 2. Impervious surfaces (paving, building, and garage) averaged about 40% of lot area in block 1 and 62% in block 2. This difference reflects the higher building densities and smaller pervious surfaces in block 2.

Residential buildings and residents

The front of most residential buildings was oriented to the south or the north due to the subdivision layout. Although one and two storey homes occurred in both blocks, two storey buildings were most common. Conditioned floor area (CFA) ranged from 170 m^2 to 470 m^2 for block 1 (mean=276 m^2), and from 75 m^2 to 400 m^2 for block 2 (mean=200 m^2). All the residences inventoried in block 1 were single family, and the number of occupants ranged from 1 to 4. Block 2 was composed of 1–4 family residential buildings, with occupant numbers ranging from 1–17 per building. Based on the interviews, residents in block 1 had more education and higher income than those in block 2.

Building energy consumption

Average annual energy consumption per residence in block 1 was about 10·3±0·8 (standard error) Wh/CDD/m^2 of CFA for cooling, and 194·0±19·1 kJ/HDD/m^2 for heating. In block 2, the annual energy consumption averaged 9·4±1·3 Wh/CDD/m^2 for cooling, and 154·9±1·4 kJ/HDD/m^2 for heating. Cooling or heating degree days (CDD or HDD) are measures of how cold or hot it is on any given day, relative to a base temperature of 18·3°C (65°F). The degree days indicate energy requirements over the long term. The CDD and HDD in Chicago averaged 922 and 6153 per year, respectively (calculated by use of Fahrenheit unit), based on a MICROPAS weather file used for building energy simulations in this study (see below).

The annual heating energy use in block 1 was about 25% greater than in block 2, although there is little difference in the cooling energy use between the two blocks. In general, studies have found that energy use increases with occupant income and building size (City of Chicago, 1992; US Department of Energy, 1993). Therefore, it is not surprising that energy use was greater in block 1, where income was higher and building floor area was greater, than in block 2.

Modeling of indirect carbon reduction by vegetation

Computer programs

The effects of trees on indirect carbon reduction through savings of building heating and cooling energy were modeled using two computer simulation programs, SPS (McPherson *et al.*, 1985, 1988; McPherson, 1990, 1994) and MICROPAS (Nittler and Novotny, 1983; McPherson *et al.*, 1988; McPherson, 1990, 1994; ENERCOMP, Inc., 1995). SPS (Shadow Pattern Simulator) creates MICROPAS-compatible hourly shading coefficients for entire building surfaces from the shading of a tree. The SPS uses sun-tree-building geometry to compute the surface shading coefficients for each specified month, day, and hour.

MICROPAS estimates hour-by-hour building energy use based on the building's thermal characteristics, occupant behavior, and specific weather data. The MICROPAS accepts SPS results to reduce solar radiation on building surfaces resulting from tree shade. A MICROPAS-compatible local weather file (by ENERCOMP) including hourly temperature, radiation and wind speed data is loaded to the MICROPAS to accomplish its simulation. It is used widely by architects, engineers, and utilities to evaluate building energy performance. The California Energy Commission (1992) has certified MICROPAS for checking building compliance with state energy-efficiency standards.

Base case buildings

Data on dimensions of buildings were collected in all residential lots. Representative prototype buildings were created so that they could match building types in the study blocks. Three different building types for each study block were selected for building energy simulations. For block 1, square buildings of different sizes and numbers of stories were simulated: 1-storey large (15 m × 15 m), 2-storey small (7·5 m × 7·5 m), and 2-storey large (15 m × 15 m) buildings. For block 2, rectangular buildings of similar sizes (7·5 m × 15 m) but different orientations and numbers of stories were simulated: 1-storey NS orientation, 1-storey EW orientation, and 2-storey NS orientation buildings. Height of all the buildings was 3 m for 1 storey and 6 m for 2 storey.

A MICROPAS file for each prototype building was prepared using base case building characteristics, as shown in Table 1. Detailed input data for MICROPAS parameters were collected from one residential building in each prototype, selected for accessibility for data collection.

Energy performance validation

A close match between energy performance of the base case building and its actual building indicates that simulations produce realistic data on energy use. Two-year metered energy consumption data (April 1991 through March

Table 1. Base case building characteristics as input data for MICROPAS simulations

Building feature	Block 1			Block 2	
	1 storey, large	2 storey, small	2 storey, large	1 storey	2 storey
Construction type	Brick	Brick	Brick	Brick	Brick
Year built	1940–1960	1940–1960	1940–1960	1950–1960	1950–1960
No. units (occupants)	1 (3)	1 (2)	1 (4)	1 (2)	2 (6)
Energy-use intensity					
Heating (kJ/HDD/m^2)	150·6	230·8	200·8	152·3	158·2
Cooling (Wh/CDD/m^2)	9·9	8·9	12·0	7·9	12·6
Conditioned floor area (m^2)	197	181	331	132	190
Volume (m^3)	542	496	959	363	521
Front orientation	North	South	South	North	South
Window area (m^2)					
North	7	4	12	3	3
East	9	5	10	6	8
South	6	7	9	4	7
West	3	6	20	3	6
Total	25	22	51	16	25
Floor area	12·7	12·0	15·5	11·9	13·0
Window panes (no., *U*-value)	2, 3·41	2, 3·69	2, 3·69	2, 2·50	2, 2·50
Window shading coefficient					
Glass only	0·88	0·88	0·88	0·88	0·88
Drapes or blinds	0·78	0·78	0·78	0·78	0·78
Duct insulation (*R*-value)	0·74	0·35	0·35	0·74	0·74
Wall insulation (*R*-value)	1·25	1·25	1·25	1·25	1·25
Attic insulation (*R*-value)	3·35	3·35	3·35	6·69	6·69
Crawlspace/basement					
Floor (*R*-value)	0·70	0·70	0·70	1·41	0·70
Stem wall (*R*-value)	0·88	0·88	0·88	0·88	0·88
Infiltration (air change/h)	0·56	0·90	1·11	0·54	0·90
Local shielding class	3	4	4	3	4
Latent heat fraction	0·1	0·1	0·1	0·1	0·1
Glazing obstruction	0·7	0·7	0·8	0·65	0·7
Wind correction factor	0·25	0·4	0·4	0·25	0·4
Internal gain (kJ/h)	54 732	51 915	77 474	43 495	74 552
Gas furnace efficiency	0·60	0·55	0·58	0·67	0·60
Air conditioner (SEER)	7·8	8·0	6·7	8·9	6·6
Thermostat settings	No setback	No setback	No setback	No setback	No setback
Summer cooling (°C)	25·6	26·7	26·7	26·1	25·6
Winter heating (°C)	21·1	22·2	22·2	21·1	21·1

HDD and CDD: Heating and cooling degree days. Unit of *U* and *R*-value: W/m^2 K and m^2 K/W. SEER: Seasonal energy efficiency ratio.

1993) for a sample of 18 residences in the study blocks were obtained with the residents' approval from Commonwealth Edison and Peoples Gas (suppliers of electricity and natural gas, respectively). Data on heating and cooling degrees for the two years were also collected from the local utilities. Average energy consumption from actual buildings of each type was used to calculate annual heating and cooling intensities for each base-case building.

To match modeled energy use to metered energy use in each base case building, the various input parameters were adjusted slightly through iterative runs of the MICROPAS. Comparisons of similarity were made using a Heating Performance Index (HPI) and Cooling Performance Index (CPI) that partially normalize for different weather conditions and building sizes (Mahajan *et al.*, 1983). The HPI and CPI were calculated as:

$$\mathrm{HPI}=\mathrm{AH}/\mathrm{HDD}/\mathrm{CFA}$$

$$\mathrm{CPI}=\mathrm{AC}/\mathrm{CDD}/\mathrm{CFA}$$

where AH = annual total of natural gas consumed for space heating in kJ, AC = annual total of electricity consumed for space cooling in Wh, and CFA = conditioned floor area in m^2.

Shading effect

Data on the number, size, and location of trees around buildings were collected in all residential lots to model the shading effects. Total and crown height of trees was measured using an altimeter. A tape was used to measure crown diameter. Tree planting potential also was surveyed in the field for the sample of 33 residential lots, to obtain a realistic estimate of the number and mature size of trees that could be planted on all four sides of each building. The planting potential included only trees 3 m or more in crown diameter which can be grown without interfering with present above ground utility lines.

Representative tree configurations were created so that they could match tree characteristics in the study blocks. Three tree sizes (small, medium, and large) and three planting distances from building (3·6, 6·6 and 10·2 m) were typified for simulation purposes (Table 2 and Figure 1). Seven planting directions from building (north-east, east, south-east, south, south-west, west, and north-west) also were simulated based on initial analysis of solar paths. Small and medium trees were located at a distance of 3·6 m from building, small, medium and large trees at 6·6 m, and only large trees at 10·2 m. A total of 42 SPS input files (seven directions × six cases of sizes and distances) were created for each prototype building. All the shade trees were assumed to be deciduous, because most of the shade trees in the study blocks were deciduous (about 95%). Their crowns were assumed to transmit 15% of incoming radiation during the in-leaf period (May to October) and 75% of radiation when leaves were absent (McPherson, 1984; McPherson *et al.*, 1993b).

A total of 42 SPS output files were run with each prototype building MICROPAS file to alter solar radiation on building surfaces for an energy analysis of the effects of different sizes, distances and directions of trees. The MICROPAS used a full-year Chicago weather file provided by ENERCOMP to perform hour-by-hour heatflow and zone load energy calculations. A total of 252 (42 shading

Table 2. Tree characteristics as SPS input data

Parameter	Size		
	Small	Medium	Large
Crown diameter (m)	3·6	7·2	10·8
Crown height (m)	5·4	8·4	11·4
Bole height (m)	1·8	2·4	3·6
Tree height (m)	7·2	10·8	15·0
Shape	Paraboloid	Paraboloid	Paraboloid
Summer shading coefficient[a]	0·15	0·15	0·15
Winter shading coefficient[a]	0·75	0·75	0·75

[a] Fraction of irradiance transmitted through tree crown (McPherson, 1984; McPherson *et al.*, 1993b).

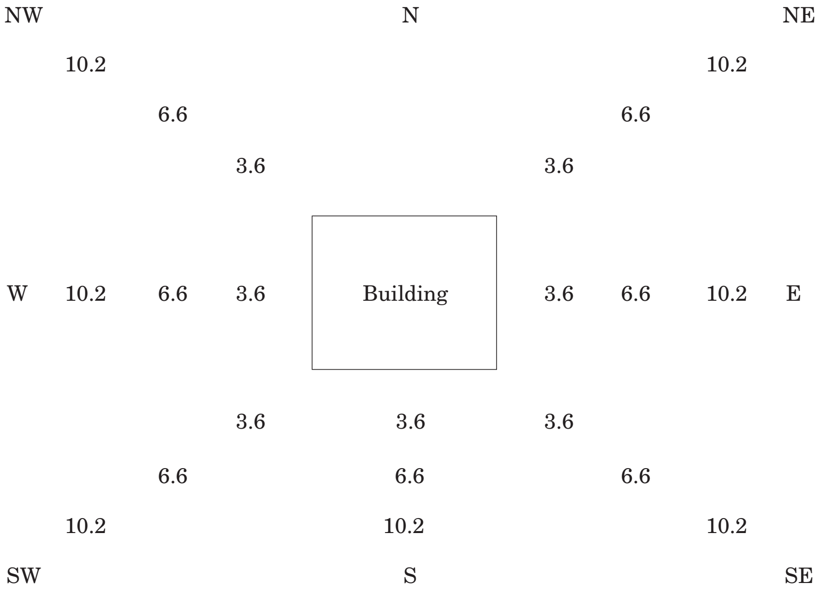

Figure 1. Distance and directional coordinates of shade trees from residential building (the figures indicate distances in meters from building).

scenarios × six prototype buildings) SPS and MICROPAS files were thus created to accomplish the simulation purposes. Energy saving of a shade tree around a prototype building was extrapolated to similar shade trees (in terms of size and location) around similar residential buildings.

Evapotranspiration and wind-reduction effect

Evapotranspirational (ET) and wind-reduction effects result from the aggregate impacts of all neighborhood vegetation, not just the trees directly shading the building. Existing research (Huang *et al.*, 1987; Profous, 1992) reports that a 10% increase in vegetation cover decreases summer temperature by 0·5 to 1°C. There was a difference of about 20% in vegetation cover between the two study blocks (block 1: 58·9%, block 2: 36·3%), when trees, shrubs, and lawns were included. Based on the existing research, it was expected that block 1 is at least 1°C cooler than block 2.

To confirm this expectation, temperatures were measured at 25 to 30 random spots in each block with a portable temperature-measuring instrument, at 3-h intervals from 5·40 am to 6·20 pm on a sunny day in middle summer. The measurement revealed that temperature in block 1 was about 1°C cooler during noon to midafternoon than in block 2 (although this measurement might not represent daytime temperatures during whole summer period). Based on these observed temperature differences, hourly summertime temperatures in the MICROPAS weather file were lowered in a graduated manner to account for the diurnal differences in block 1. Morning temperatures were altered the least because temperature differences were small, while mid-afternoon temperatures were reduced by a maximum of 1°C. Night-time temperatures were unaltered. This weather file was run with each base case MICROPAS file to calculate the amount of energy savings attributable to ET cooling in block 1.

Results from studies of wind reduction in residential neighborhoods suggest that a 10% increase in tree cover reduces windspeed by 5 to 15%, depending on the housing density (Heisler, 1990; Myrup *et al.*, 1993). The magnitude of windspeed reduction associated with a 10% increase in tree cover is greater for neighborhoods with relatively low tree canopy cover than for those with high tree cover.

MICROPAS uses local building shielding classes to incorporate the effects of buildings and vegetation on air infiltration rates in houses (ENERCOMP, Inc., 1995). Based on tree cover in the study area, conservative windspeed reductions of 10 (block 2) to 20% (block 1) were simulated by increasing the building shielding class for base case MICROPAS files. Heating energy savings associated with increased shielding were attributed to the aggregate effects of local tree cover in the study blocks.

Conversion of building energy to carbon

The power source for heating energy in Chicago was natural gas supplied by Peoples Gas, while cooling energy was electricity from nuclear power (83·5%) and fossil fuels (16·5%) generated by Commonwealth Edison. Heating and cooling energy was converted to an estimate of carbon emitted based on a ratio of about 0·0122 kg carbon per MJ (pers. comm. with Peoples Gas), and 0·0511 kg carbon per kWh (pers. comm. with Commonwealth Edison).

Results and discussion

Energy performance validation

MICROPAS algorithms have been validated and found to agree closely with data from occupied houses and passive test cells (Atkinson *et al.*, 1983). To validate the energy performance of MICROPAS simulations in this study, the HPI's and CPI's of the base case buildings modeled were compared with those of their respective actual buildings in the study area. The HPI's and CPI's of the base-case buildings modeled were, respectively, within 3·5% and 6·0% of their real reference buildings (Table 3).

Effects of vegetation on indirect carbon reduction

Shading effect

The shading effects on the reduction of carbon emission were influenced by size, direction, and distance of shade trees around building as well as building type. A large shade tree (10·8 m in crown diameter) located at a distance of 6·6 m from the east or west wall of buildings provided the greatest carbon reduction through cooling energy savings, a reduction of 7–8%. However, most of the existing shade trees increased heating energy use by reducing solar heat gain during the winter. Large trees located close to the south wall were projected to increase heating energy use by 1–2%. Other studies also found that the greatest cooling saving came from a tree on the west, whereas a south tree could increase heating energy use (Minnesota Department of Natural Resources, 1991; McPherson *et al.*, 1993b; McPherson, 1994).

The existing shade trees in most of locations modeled increased carbon emissions from the combined change in heating and cooling energy use. A large tree located at a distance of 6·6 m and a tree of medium size at 3·6 m from the south wall caused the greatest net increase in carbon emissions (average = 0·9%) for the six prototype buildings. This net increase in carbon emissions resulted from tree planting in locations where the winter shade increases carbon emissions from heating energy use more than the summer shade reduces carbon emissions from cooling energy use. Also, annual carbon emissions associated with heating the prototype buildings were about 28 times greater than the emissions related to cooling. This result is

Table 3. Energy performance validation of MICROPAS modeling for base case buildings

Block	Building	HPI[a]			CPI[b]		
		Actual	Modeled	% diff.	Actual	Modeled	% diff.
1	1 storey, large	150·6	147·4	2·1	9·89	10·45	5·7
	2 storey, small	230·8	223·0	3·4	8·93	9·47	6·0
	2 storey, large	200·8	193·8	3·5	11·95	12·59	5·4
2	1 storey	152·3	147·9	2·9	7·86	8·33	6·0
	2 storey	158·2	153·0	3·3	12·64	13·30	5·2

[a] Heating Performance Index (kJ/heating degree days/m^2 of conditioned floor area).
[b] Cooling Performance Index (Wh/cooling degree days/m^2 of conditioned floor area).

somewhat unique to Chicago, due to the large amount of cooling energy provided by nuclear power (83·5%) and the long heating season. If cooling energy had been generated by fossil fuels and the heating season had been shorter, the shading effects on the reduction of carbon emission would be greater. All the shade trees on the northeast and northwest and large trees on the west did not show a significant increase in carbon emission.

Table 4 shows the effects of all shade trees on annual energy savings and reduction of carbon emission per CFA for each prototype building in the study blocks. In block 1, energy savings from all shade trees around residential buildings averaged about 7·2± 1·9% (standard error) for cooling and −1·2± 0·3% for heating. In block 2, energy savings from the shading effects averaged 0·6±0·2% for cooling and −0·2±0·0% for heating. Peak cooling energy saving is important to utilities because peak power is expensive to provide. During peak days when air conditioning loads are greatest, more power is generated with fossil fuels. Average energy saving for peak cooling was about 3·5±0·9% in block 1 and 0·4±0·1% in block 2. Total reduction of carbon emission per CFA from all shade trees averaged −141±30 g/m^2 in block 1 and −14±4 g/m^2 in block 2.

On the whole, residential units with more trees had more cooling energy savings, but greater heating energy requirement. Tree shading provided an average reduction of 7% in carbon emission for cooling in block 1, but this was offset by increased heating due to decreased solar gain during the winter. Shade trees planted on the east, south-east, south and south-west around buildings, which caused a negative effect on total reduction of carbon emission, accounted for 55% of all shade trees in block 1 and 68% in block 2. To minimize negative effects of tree shading on indirect carbon reduction, trees must be planted in appropriate locations (e.g. close to the west wall). Trees used in simulations of the shading effects were all deciduous. Conifers, which do not shed their leaves during the winter, may cause more negative effects on heating energy savings.

Evapotranspiration and wind-reduction effect

Evapotranspiration by vegetation was projected to provide an average saving of 8·0±0·3% in cooling energy for the three prototype buildings in block 1 (Table 5). There was no ET effect on heating energy. For peak cooling energy, the mean saving was estimated to be 5·8±0·3%. Total reduction of carbon emission from the energy saving averaged 38±2 g/m^2 of CFA across the prototype buildings (Table 5).

Heating energy saving attributed to windspeed reduction averaged 4·5±0·1% for the prototype buildings in block 1 and 2·6±1·0% in block 2 (Table 6). Windspeed reduction also saved cooling energy by about 1% and peak cooling energy by approximately 2% in both blocks. In block 2, no savings from windspeed reduction were projected for 2-storey buildings due to little wind shielding for the second floor. Windspeed increases as a function of height (ENERCOMP, Inc., 1995). Therefore, taller buildings have more infiltration and more natural ventilation. Avoided

Table 4. Effects of all shade trees on annual space conditioning energy saving and reduction of carbon emission per conditioned floor area for each prototype building in study blocks

Block	Prototype building	Mean energy saving (%)			Mean total carbon reduction (g/m^2)
		Heating	Cooling	Peak cooling[a]	
1	1 storey, large (N=5)	−1·9 (0·6)	10·9 (3·6)	4·1 (1·3)	−163 (50)
	2 storey, small (N=7)	−0·7 (0·2)	1·0 (0·4)	0·6 (0·2)	−124 (24)
	2 storey, large (N=10)	−1·3 (0·4)	9·6 (3·1)	5·2 (1·6)	−142 (45)
	Grand mean (N=22)	−1·2 (0·3)	7·2 (1·9)	3·5 (0·9)	−141 (30)
2	1 storey, NS-oriented (N=7)	−0·1 (0·0)	0·0 (0·0)	0·0 (0·0)	−8 (2)
	1 storey, EW-oriented (N=4)	−0·1 (0·0)	2·1 (0·9)	2·4 (1·0)	−8 (3)
	2 storey (N=17)	−0·3 (0·1)	0·6 (0·2)	0·1 (0·0)	−18 (5)
	Grand mean (N=28)	−0·2 (0·0)	0·6 (0·2)	0·4 (0·1)	−14 (4)

Negative values indicate increase of heating energy use and net increase in carbon emission due to winter shade. Standard error is given in parenthesis.

[a] 4 pm, July day 1.

Table 5. Evapotranspiration effect of vegetation on annual space conditioning energy saving and reduction of carbon emission per conditioned floor area for each prototype building in study block 1

Prototype building	Energy saved (%)			Total C reduced (g/m^2)
	Heating	Cooling	Peak cooling[a]	
1 storey, large	0·0	7·9	6·1	37
2 storey, small	0·0	8·6	6·1	36
2 storey, large	0·0	7·5	5·1	42
Mean	0·0	8·0	5·8	38
SE[b]	0·0	0·3	0·3	2

[a] 4 pm, July day 1.
[b] Standard error.

total carbon release from the energy savings averaged 659 g/m^2 of CFA (a 4·3% reduction of base case) across the prototype buildings in block 1 and 306 g/m^2 (a 2·5% reduction) in block 2. The total indirect carbon reduction per CFA due to wind reduction by trees in block 1 was about two times greater than in block 2.

Aggregate indirect carbon reduction

Average annual reduction of carbon emission due to shading, ET, and windspeed reduction ranged from 3·2 to 3·9% (reduction of 380 to 670 g/m^2 of CFA) for the building types in block 1, and from −0·2 to 3·8% (reduction of −20 to 450 g/m^2) in block 2 (Table 7). Total annual reduction of carbon emission for all residential buildings was projected to be approximately 3490 kg in block 1 (shading: −864 kg, ET: 241 kg, windspeed reduction: 4114 kg) and 510 kg in block 2 (shading: −88 kg, windspeed reduction: 594 kg). The

Table 6. Projected effect of windspeed reduction by vegetation on annual space conditioning energy saving and reduction of carbon emission per conditioned floor area for each prototype building in study blocks

Block	Prototype building	Energy saved (%)			Total C reduced	
		Heating	Cooling	Peak cooling[a]	%	g/m^2
1	1 storey, large	4·4	1·5	2·3	4·3	510
	2 storey, small	4·3	1·3	2·2	4·2	757
	2 storey, large	4·7	0·9	1·8	4·5	711
	Mean	4·5	1·2	2·1	4·3	659
	SE[b]	0·1	0·1	0·1	0·1	62
2	1 storey, NS	3·9	1·0	2·4	3·8	458
	1 storey, EW	3·9	1·7	2·4	3·8	461
	2 storey	0·0	0·0	0·0	0·0	0
	Mean	2·6	0·9	1·6	2·5	306
	SE[b]	1·0	0·4	0·6	1·0	125

[a] 4 pm, July day 1.
[b] Standard error.

Table 7. Aggregate effects of shading, evapotranspiration and windspeed reduction by vegetation on annual reduction of carbon emission for each prototype building in study blocks

Block	Prototype building	Total CFA (m^2)	Carbon reduction		
			Mean (%)	Mean/CFA(g/m^2)	Total (kg)
1	1 storey, large	1284	3·2 (0·4)	384 (55)	493
	2 storey, small	1323	3·8 (0·2)	669 (24)	885
	2 storey, large	3459	3·9 (0·4)	611 (57)	2113
	Block total				3491
2	1 storey, NS	863	3·7 (0·0)	450 (5)	388
	1 storey, EW	432	3·8 (0·1)	453 (10)	196
	2 storey	4314	−0·2 (0·1)	−18 (9)	−78
	Block total				506

CFA: Conditioned floor area. Negative values indicate increase of heating energy use and net increase in carbon emission due to winter shade. Standard error is given in parenthesis.

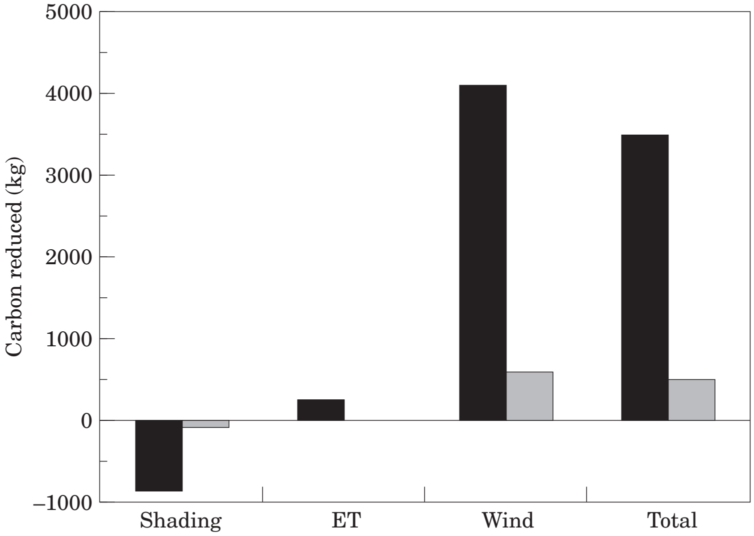

Figure 2. Aggregate effects of shading, evapotranspiration and windspeed reduction on total annual reduction of carbon emission in study blocks. Block 1, ■; Block 2, ▨.

effect of windspeed reductions greatly contributed to the reduction of carbon emissions from power plants, while shading increased carbon emissions (Figure 2). The total annual reduction averaged 158·7 ± 12·8 kg per residence in block 1 and 18·1 ± 5·4 kg per residence in block 2.

Planting strategies

To maximize indirect carbon reduction by residential vegetation in Chicago, the following planting strategies are suggested. The planting strategies also can be applied to other mid and high-latitude cities which have a relatively long heating season.

Planting on the west

The best place to locate trees for minimizing carbon release through energy savings was opposite west facing windows and walls. Planting in this direction will obstruct solar gain in the afternoon during the summer. Large trees should be located close to the west wall for optimum shading.

Avoidance of planting on the east and south

Tree planting on the east considerably reduced air conditioning demand during the summer by blocking solar gain in the morning, but, had adverse effects on heating energy use. Shade trees located on the south, south-east, and south-west also caused significant net increases in carbon release. They increased the demand of heating energy during the winter season through solar gain obstruction, particularly in Chicago which has many more heating degree days than cooling degree days. Only shrub planting along the east and south boundary of yards will likely reduce carbon emissions. If residents wish to plant trees in these directions, solar-friendly trees must be selected. Solar-friendly trees are deciduous trees that possess relatively open crowns when out of leaf, leaf out late in spring, and drop their leaves early in fall. For the Chicago area, they include: *Celtis occidentalis*, *Crataegus punctata*, *Fraxinus americana*, *F. pennsylvanica*, *Ginkgo biloba*, *Gleditsia triacanthos* var. *inermis*, *Metasequoia glyptostroboides*, *Populus tremuloides*, *Sophora japonica*, and *Tilia cordata* (Ames, 1987; Watson, 1991).

Dense planting on the north, north-east and north-west

Dense tree planting on the north, north-east, and north-west is recommended to maximize indirect carbon reduction through wind-reduction and evapotranspiration effects in the neighborhood. The number of new potential plantings on the north and west in

Table 8. Tree planting potential by tree size to maximize indirect carbon reduction in study blocks (in number of trees)

Block		North			West			Total		
		Small	Medium	Large	Small	Medium	Large	Small	Medium	Large
1	Total	39	28	8	29	8	2	68	36	10
	Mean	2	1	0	1	0	0	3	2	0
	SE	0	0	0	0	0	0	1	0	0
2	Total	46	15	0	11	0	0	57	15	0
	Mean	2	1	0	0	0	0	2	1	0
	SE	0	0	0	0	0	0	0	0	0

Standard tree sizes are shown in Table 2. Mean: Number of trees per residence. SE: Standard error.

the study blocks averaged two or three per residence for small trees and 1 or 2 per residence for trees of medium size (Table 8). In Chicago, prevailing winds blow from the north or west during the winter season (NOAA, 1993). The use of evergreen shrubs or hedges on north walls will reduce heat conduction from, and cold-wind infiltration into the interior of buildings.

The new tree planting recommended in Table 8 could triple present tree cover in block 2, which currently has tree cover characteristic of residential lands of Chicago. The increase in tree cover could result in indirect carbon reduction of about 4600 kg per year, nine times more than the reduction associated with present planting in block 2.

Reduction of impervious surfaces and relocation of above ground utility lines

The present impervious surfaces should be decreased to improve tree planting in the north direction. In block 2, there was little planting space for street trees due to the wide sidewalk along Byrn Mawr Avenue located in the north of the block. Reducing impervious cement areas in back yards also will result in increased space for tree planting. Above ground utility lines could be relocated to the boundary of the yards or below ground to allow proper space for tree growth.

Minimization of adverse shading effect on adjacent properties

Tree planting on one property could impact surrounding properties. If a large tree is planted on the north or west wall to reduce carbon emissions, the same tree may be on the south or east of a neighbor and increase carbon emissions on that property. This adverse shading effect on the adjacent property should be minimized by selecting proper species and sizes of trees (e.g. solar-friendly or smaller trees) at the planning stage.

Conclusion and implication

Carbon dioxide is a major greenhouse gas that contributes to the greenhouse effect and climate change. This study applied computer simulations to quantify shading, evapotranspiration, and wind-reduction effects of existing vegetation on indirect carbon reduction for residential neighborhoods in Chicago. For purposes of detailed quantification, the spatial scale of this study was limited to two residential blocks having a significant difference in vegetation cover. This study breaks new ground by calculating carbon reduction once the associated energy performance effects are known.

The results of this study imply that urban vegetation has the potential to make an important contribution to the reduction of atmospheric carbon, although it is only part of a solution to minimize the risks of climate change. The residential landscapes of the study area were mainly composed of relatively small trees. As trees grow, the amount of indirect carbon reduction from evapotranspiration and windspeed reduction might gradually be increased. Tree shade increased carbon emissions due to many trees in the wrong locations (e.g. south walls) that increase heating energy use during the winter through solar gain obstruction. This result is specific to Chicago, due in part to a relatively long heating season and clean, nuclear-generated cooling energy. Carbon emission reduction from shading is likely to be substantial in regions where the cooling season is long and coal is the main source for cooling energy. Planting in optimum locations and proper selection of tree species are essential in avoiding a negative shading effect. This study suggested appropriate planting strategies to minimize energy consumption and carbon emissions to the atmosphere. The planting strategies based on simulations of indirect carbon reduction can be used for landscape designers, greenspace planners, and residents.

Computer simulations of building energy performance to quantify indirect carbon reduction were based on an actual survey of tree and building parameters, although the sample size for some data (i.e. metered energy use) was not large due to limited cooperation. This study pioneers in tackling the complexities associated with simulating actual neighborhoods instead of single building and landscape prototypes. The two residential neighborhoods contained a surprising amount of building and tree diversity. For example, it was necessary to account for various: (1) building types and sizes; (2) tree species and sizes; (3) tree-building juxtapositions; and (4) tree-climate interactions. Capturing this diversity both in the field and within the existing modeling system was a challenge.

This study went beyond estimating annual carbon reduction based on the existing tree distribution and projected potential carbon reduction obtained by planting additional trees in vacant sites. This information could be useful for evaluating the cost effectiveness of a utility-sponsored retrofit program that plants trees in strategic locations to obtain carbon offset credits. The amount of indirect carbon reduction could be regionally variable with differences in tree plantings around buildings, length in the heating and cooling season, and carbon contents of energy supplied. Therefore, the carbon estimates from this study cannot be directly transferred to other cities with even similar building structures. More studies at a regional or national scale, including multi-family residential settings, are required to deepen our understanding of effects of urban vegetation on indirect carbon reduction.

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