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Trends and scenarios of the carbon budget in postagricultural Puerto Rico (1936–2060)

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Abstract

Contrary to the general trend in the tropics, Puerto Rico underwent a process of agriculture abandonment during the second half of the 20th century as a consequence of socioeconomic changes toward urbanization and industrialization. Using data on land-use change, biomass accumulation in secondary forests, and ratios between gross domestic product (GDP) and carbon emissions, we developed a model of the carbon budget for Puerto Rico between 1936 and 2060. As a consequence of land abandonment, forests have expanded rapidly since 1950, achieving the highest sequestration rates between 1980 and 1990. Regardless of future scenarios of demography and land use, sequestration rates will decrease in the future because biomass accumulation decreases with forest age and there is little agricultural land remaining to be abandoned. Due to high per-capita consumption and population density, carbon emissions of Puerto Rico have increased dramatically and exceeded carbon sequestration during the second half of the 20th century. Although Puerto Rico had the highest percent of reforestation for a tropical country, emissions during the period 1950–2000 were approximately 3.5 times higher than sequestration, and current annual emission is almost nine times the rate of sequestration. Additionally, while sequestration will decrease over the next six decades, current socioeconomic trends suggest increasing emissions unless there are significant changes in energy technology or consumption patterns. In conclusion, socioeconomic changes leading to urbanization and industrialization in tropical countries may promote high rates of carbon sequestration during the decades following land abandonment. Initial high rates of carbon sequestration can balance emissions of developing countries with low emission/GDP ratio. In Puerto Rico, the socioeconomic changes that promoted reforestation also promoted high-energy consumption, and resulted in a net increase in carbon emissions.

Keywords: carbon budget, globalization, Kyoto protocol, land-use change, Puerto Rico, secondary succession, STELLA

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Introduction

Quantifying trends in carbon budgets has become an urgent research objective, given that carbon fluxes to the atmosphere are increasingly recognized as major drivers of climatic change (Nakicenovic *et al*., 2000; Watson *et al*., 2000). In the context of international initiatives promoting emissions reduction and carbon mitigation (e.g. Kyoto protocol), countries are the most significant political and decision-making units. Therefore, assessing trends in carbon budget at a country level is a priority (Niles *et al*., 2002), particularly in the tropics where such information is scarce, limited to short time periods, and restricted to countries or regions where deforestation dominates the carbon balance (e.g. South East Asia, Houghton & Hackler, 1999; Brazil, Schroeder & Winjum, 1995; China, Wang *et al*., 2001).

In most tropical regions, characterized by agricultural expansion and increasing human population, land-cover

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change is dominated by deforestation (Turner *et al.*, 1990), the second most important source of CO_2 to the atmosphere, only exceeded by fossil fuel emissions (Houghton, 1999; Fearnside, 2000). In contrast, in developed countries where the production base has shifted from traditional agriculture to manufacturing and intensified agriculture, forests are expanding and acting as carbon sinks (Waggoner & Ausubel, 2001). The majority of forest recovery is occurring in northern temperate and boreal ecosystems (Mynani *et al.*, 2001), regions that include intense urbanization (UNCHS, 1996) and the highest levels of carbon emissions (Nakicenovic *et al.*, 2000).

There are some examples of forest expansion in the tropics, and probably the most dramatic is Puerto Rico. In the late 1940s, postwar changes in the political status of Puerto Rico resulted in an influx of capital from the USA promoting industrialization (Dietz, 1986), which in turn promoted population migration from rural to urban areas and abandonment of agriculture lands (Cruz Baez & Boswell, 1997). Consequently, between 1950 and 1990, Puerto Rico had the highest rate of reforestation in the world (Rudel *et al.*, 2000) and a high rate of urban expansion (Thomlinson *et al.*, 1996; Thomlinson & Rivera, 2000; Lopez *et al.*, 2001).

Although reforestation is far less common than deforestation in tropical countries, it is not unique to Puerto Rico. Forest recovery occurs in regions where marginal agricultural areas are being abandoned such as the mountains of the Dominican Republic (Zweifler *et al.*, 1994), Northeastern Brazil (Moran *et al.*, 1996), areas of the South American Andes (Preston, 1996), Taiwan (Chang & Tsai, 2002), the Republic of Palau (Endress & Chinea, 2001), and peninsular Malaysia (Brookfield, 1994). Forest recovery due to land abandonment may become more widespread in the coming decades as human population growth rate declines (Lutz *et al.*, 2001) and economic globalization stimulates urbanization (UNCHS, 1996.)

Forest recovery on abandoned agricultural areas is an important carbon sink, and this process provides opportunities to increase future carbon sequestration (Brown & Lugo, 1992; Brown *et al.*, 1997; Silver *et al.*, 2000). To assess the overall impact of forest recovery on the carbon budget, it is also necessary to quantify the change in emissions derived from the socioeconomic processes that drive land abandonment (e.g. industrialization, increase in employment opportunities, and increase in consumption). Although the socioeconomic changes that cause land abandonment in a region may occur in a few years, forest regrowth and the associated carbon sequestration will occur over longer time periods. Consequently, the analyses of carbon budgets that include ecosystem responses to socioeconomic changes require long-term assessments (e.g. Houghton & Hackler, 1999; De Jong *et al.*, 2000; Liski *et al.*, 2000; Liu *et al.*, 2000).

The recent environmental history of Puerto Rico provides a unique opportunity to assess trends in carbon budget in a tropical environment. Specifically, we analyze the effects of socioeconomic changes in enhancing carbon sequestration due to large-scale land-use change, and compare carbon sequestration with carbon emissions due to energy consumption. Six decades of frequent aerial photograph surveys have allowed detailed descriptions of patterns in land-cover change since the late 1930s (e.g. Thomlinson *et al.*, 1996; Pascarella *et al.*, 2000; Helmer *et al.*, 2002) and chronosequence analyses of changes in forest structure after abandonment in different ecological zones (Aide *et al.*, 1995, 1996, 2000; Rivera & Aide, 1998; Zimmerman *et al.*, 1995; Pascarella *et al.*, 2000; Marcano-Vega *et al.*, 2002; Thompson *et al.*, 2002). In addition, Puerto Rico has good statistical data on population and land uses in comparison with other Neotropical countries (Cruz Baez & Boswell, 1997).

In this study, we use information on land use, land cover and forest structure to model trends in carbon stocks and fluxes as a function of land abandonment, demographic changes, and consumption patterns. We use the model for three specific goals:

1. to quantify the changes in carbon stocks and carbon sequestration rates in Puerto Rico between 1936 and 2000 as a consequence of land-cover changes, with particular emphasis on agricultural abandonment and forest succession;
2. to estimate sequestration rates under future scenarios of land-use change, comparing the relative importance of land abandonment and drivers of urban expansion (population growth, urban population density);
3. to compare the relative importance of different emission/gross domestic product (GDP) ratios on the carbon balance under different scenarios.

Material and methods

Study area

The island of Puerto Rico (Fig. 1) is centered at 18°15′N, 66°30′W and has an area of approximately 875 000 ha. Its rugged topography covers an elevation range from sea level to 1300 m, including a range in annual rainfall from 900 to 5000 mm, and a range of mean annual temperature from 19 to 26 °C (Ewel & Whitmore, 1973). The geology of the island includes sedimentary rocks on the North and South coasts, a karst region in the

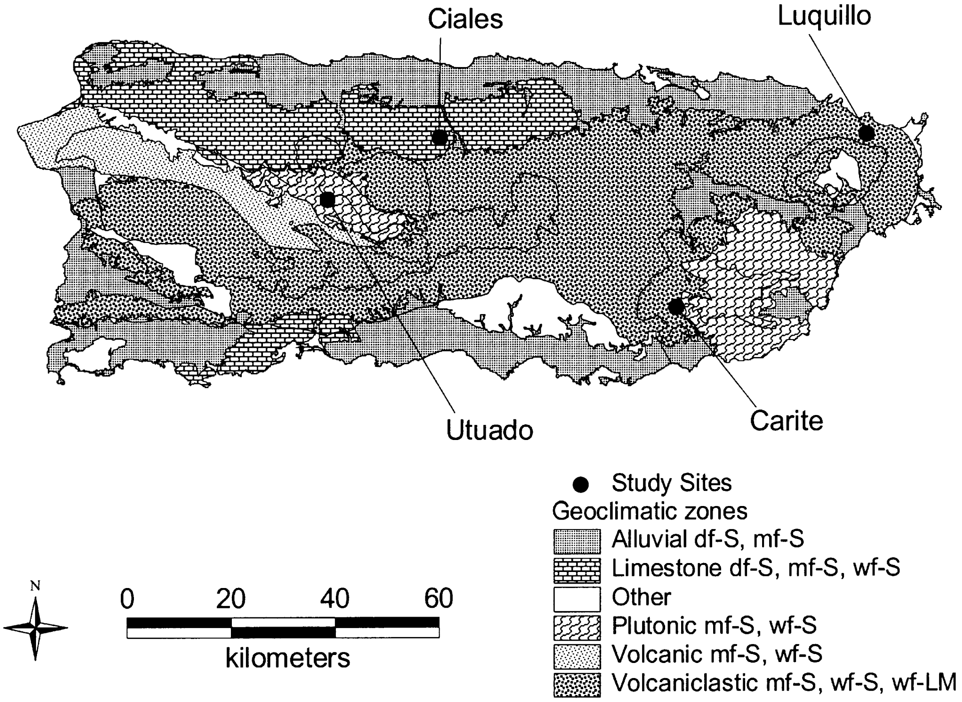

Fig. 1 Map of geoclimatic zones of Puerto Rico indicating locations of chronosequence studies of carbon sequestration though secondary succession. LM, low Montane; S, subtropical; df, dry forest; mf, moist forest; wf, wet forest.

North, sand and alluvial soils in central North and central South coastal areas, old volcanic and sedimentary (cretaceous) rocks in the central mountainous area, and some serpentine soils. In addition to human-related activities, the disturbance regime is characterized by hurricanes throughout the island, landslides in the wettest and steepest areas (Brokaw & Walker, 1991), and fires in the dry southwest (Ewel & Whitmore, 1973). Earthquakes (Nialon & Dillon, 2001) and droughts (Larsen, 2000) are other perturbations that influence the dynamics of the island ecosystem.

More than 80% of the island is included in subtropical moist and wet forest life zones (Ewel & Whitmore, 1973, Fig. 1). The secondary forests in these life zones have similar rates of recovery of forest structure and above-ground biomass (Aide *et al.*, 1995, 1996, 2000; Zimmerman *et al.*, 1995; Rivera & Aide, 1998; Pascarella *et al.*, 2000; Marcano-Vega *et al.*, 2002), similar levels of soil organic matter (Weaver *et al.*, 1987), and are dominated by the exotic *Spathodea campanulata* and the native *Guarea guidonia* (Franco *et al.*, 1997; Grau *et al.*, 2003). These life zones have experienced the greatest land-use dynamics in the last 60 years.

The dry forest life zone covers approximately 13% of the island. In the last 60 years, this area has experienced much less land-use dynamics in comparison with the moist and wet life zones, due to its continued importance as an agricultural area. Carbon sequestration rates in this life zone, based on above-ground biomass of a 50-year old secondary forest (Molina-Colon, 1998), are approximately 30% less than the average, but within the range of values reported for the wet and moist life zones (Aide *et al.*, 2000).

Until the early 1940s, Puerto Rico was similar to most Neotropical countries in which agriculture (coffee, sugar cane, tobacco, and pastures) was the base of the country's economy. Agriculture and pastures occupied close to 90% of the island during the first half of the 20th century. In 1948, the political status of Puerto Rico changed with respect to the USA, and an early consequence of this change was a sustained effort to promote light industry (Operation Bootstrap, Dietz, 1986). The change in the economic base from agriculture to manufacturing was associated with fast economic growth. For example, between 1950 and 1980 per-capita GDP, labor wages, and personal annual income all increased by a factor of 10 or more (Dietz, 1986). As a result, Puerto Rico is one of the countries with the highest per-capita income and GDP in the Neotropical region (Fig. 2). The human population increased from 1 million in 1900 to 3.7 millions in 2000. The highest annual population growth rate was 3% in 1947, and by 1990 it decreased to 1% (Cruz Baez & Boswell, 1997). Although a further decrease in population

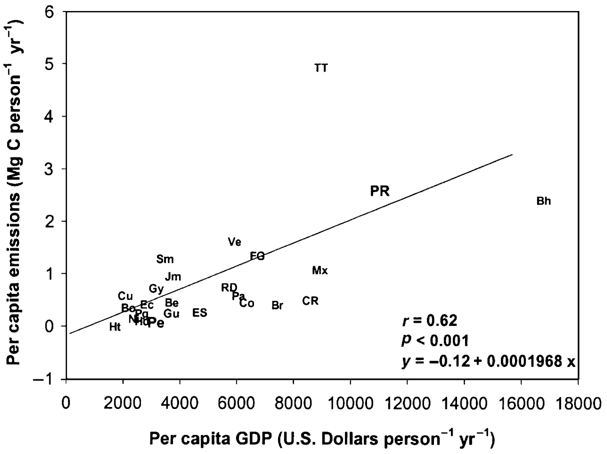

Fig. 2 Relationship between per-capita annual gross domestic product (GDP) and carbon emissions of all Neotropical countries larger than 5000 km^2 for the year 2000. Bh, Bahamas; Be, Belize; Br, Brazil; Bo, Bolivia; Co, Colombia; CR, Costa Rica; Cu, Cuba; FG, French Guyana; Ec, Ecuador; Gu, Guatemala; Gy, Guyana; Ht, Haiti; Ho, Honduras; Jm, Jamaica; Mx, Mexico; Ni, Nicaragua; Pa, Panama; Pg, Paraguay; Pe, Peru; PR, Puerto Rico; RD, Republica Dominicana; Sm, Suriname; TT, Trinidad and Tobago; Ve, Venezuela. GDP values are based on national statistics (www.cia.gov) and are computed in purchasing parity value to US dollars. Emission values are based on Marland *et al.* (2002) for all countries except Puerto Rico, which is based on estimates of the Department of Natural and Environmental Resources of Puerto Rico (DNER, 1996, 1999).

growth is possible in the future, predictions have an important level of uncertainty because the Puerto Rican population is strongly influenced by emigration to the USA (Boswell, 1985; Rivera-Batis & Santiago, 1995), and immigration from other Caribbean countries, particularly the Dominican Republic (Cruz Baez & Boswell, 1997).

From the point of view of carbon dynamics, changes in the economy of Puerto Rico since 1948 have had two major consequences. On the one hand, by increasing energy consumption, which in Puerto Rico is almost exclusively based on fossil fuels, emissions have increased to one of the highest per-capita levels in the Neotropics (Fig. 2). By the end of the 20th century, the main sources of emissions were: electric utilities (47%), transportation (34%), and industries (15%) (DNER, 1999). On the other hand, industrialization stimulated migration from rural to urban areas, which caused the abandonment of an average of approximately 10 000 ha yr^{-1} between 1950 and 1990, with a peak between 1965 and 1969 of 23 800 ha yr^{-1} (Cruz Baez & Boswell, 1997). As a consequence, between 1950 and 1990, forested area in the island increased from approximately 10–40%, the highest rate for any country during the same time period (Rudel *et al.*, 2000).

Model description

We developed a model based on STELLA graphic programming system (High Performance Systems, Inc.) version 7.03-Research (Fig. 3, Appendix A). The model estimates carbon fluxes and stocks on the basis of human population growth, GDP, and rates of change in agricultural lands. For the purposes of this study, the time range of the model was 1936 (first year of agricultural censuses and aerial photographs) to 2060, with time steps and temporal resolution of 1 year, and default options in the different procedures unless otherwise indicated. For descriptive purposes, the model is divided into three components:

(1) The land-cover component (lower and core zone in Fig. 3) includes a sequence of 'stocks' representing the area of *AGRICULTURE* (including both pastures and crops), secondary forests between 0 and 14 years old (*F014*), between 15 and 24 years old (*F1524*), between 25 and 37 years old (*F2537*), and old-growth successional forests (*OLD37*).

The *AGRICULTURE* stock is a 'reservoir' with an inflow due to agricultural expansion (*AGREXPANSION*) and an outflow representing the annual area of abandoned agricultural lands (*ABANDONMENT*), which is the product of the abandonment rate (*FARMABAND*) and a calibration coefficient (*COEFABAND*) to correct for areas which are undergoing forest succession within properties still classified as farms in census data.

Early successional forests are represented by three successive 'conveyors' with different transit times defined by periods of relatively homogeneous rates of above-ground biomass accumulation (Aide *et al.*, 2000, Fig. 4). 'Conveyors' are a type of stock that can be thought as moving sidewalks in which 'material' (hectares of abandoned land, in this case) enters, rides for a certain period of time (transit time), and moves on to the next conveyor or reservoir. After 37 years of growth, forests become *OLD37*, the final reservoir. The variable *TOTFOR* is the sum of hectares in the successional and old forest categories. Closed-canopy forest (*CCFOR*), used for comparison with satellite-based land-cover maps, includes only forests equal or older than 15 years since abandonment (*TOTFOR–F014*), and the variable *YGFOR* is the sum of the two younger forest types (*F014* and *F1524*), which are characterized by high sequestration rates (Fig. 4).

Deforestation is represented by *DEFRATE* and is the sum of the areas of *AGREXPANSION* and *URBAN GROWTH*. The proportion of total area, excluding protected areas, that is subjected to

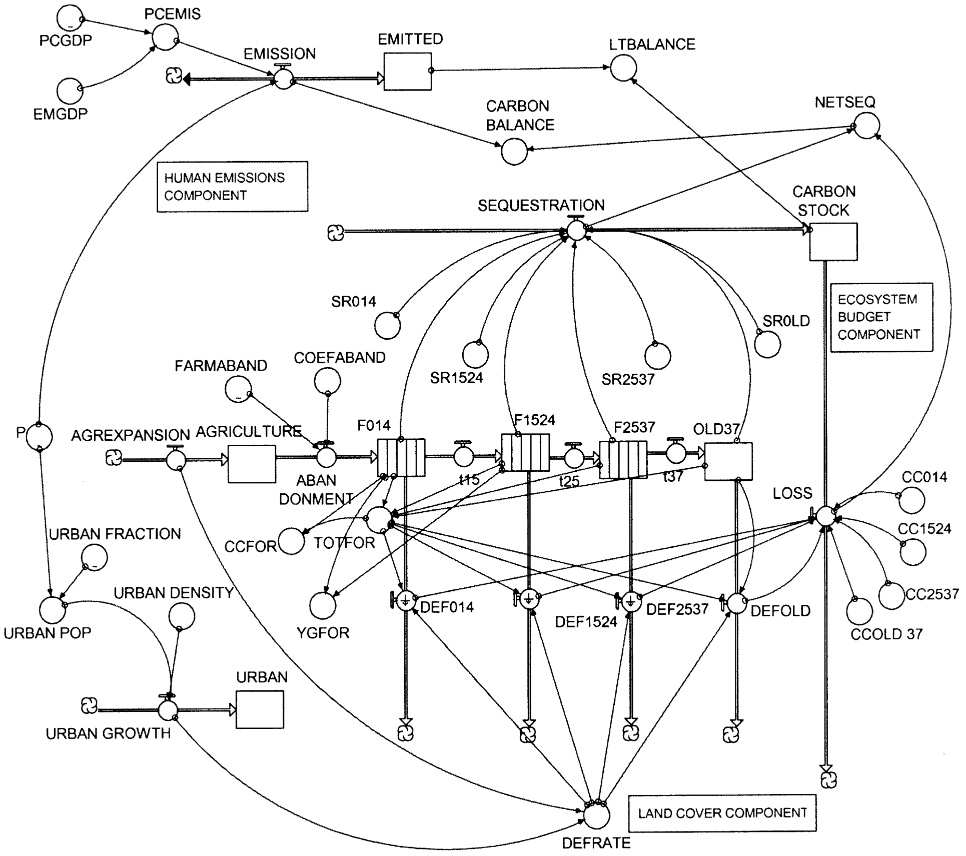

Fig. 3 Diagram of the model in STELLA graphic design. Squares represent 'stocks' of carbon or area of different land-cover types. Striped squares are 'conveyors' representing forests of different successional age. Fluxes of material or land-cover types are represented by thick arrows with attached circles. Circles are auxiliary variables ('converters'). Thin arrows represent information flows.

deforestation is applied equally to all forest age classes. In the model, *DEFRATE* can occur on 1-year-old abandoned agricultural lands. For example, urban areas that expand into agriculture lands are first abandoned and deforested in the following year of the simulation.

Urban area (*URBAN*) is a stock fed by the *URBAN GROWTH* inflow that is the product of the annual increase in urban population (*URBAN POP*) and the urban population density (*URBAN DENSITY*). *URBAN POP* is computed as the product of *P* and the proportion of *P* living in urban areas (*URBAN FRACTION*).

(2) The ecosystem budget component (Fig. 3, upper right) represents the changes in carbon stocks and flows in the island ecosystems. The *CARBON STOCK* reservoir represents the total amount of ecosystem's carbon subject to dynamic processes in the island. It is fed by the *SEQUESTRATION* inflow, computed as the summation of the products of the area of each forest class multiplied by their specific sequestration rates (*SR*). Carbon losses due to conversion of natural areas into urban and agriculture are represented by the outflow *LOSS* which is the product of the deforested area in each successional category multiplied by the specific average per-hectare carbon content (*CC*). The annual change in carbon stocks in Puerto Rican ecosystems (net sequestration) is represented by the variable *NETSEQ*, which is the difference between *SEQUESTRATION* and *LOSS*.

(3) The human emissions component (Fig. 3, upper left) estimates annual carbon *EMISSION* as the product of *P* and per-capita emissions (*PCEMIS*). In turn, *PCEMIS* is the product of the per-capita gross domestic product (*PCGDP*), and the emission of carbon per unit of GDP (*EMGDP*). The difference between carbon emission and net carbon sequestration is the *CARBON BALANCE* of the island. *EMISSION* feeds into the reservoir *EMITTED* which is the summation of total emitted carbon for the modeling period. The difference between *EMITTED* and *CARBON STOCK* defines the long-term carbon balance (*LTBALANCE*).

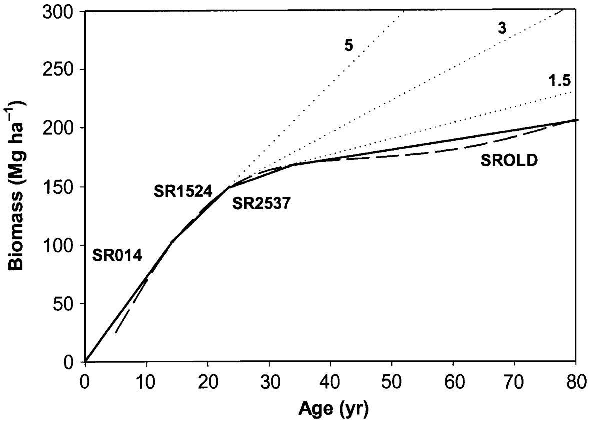

Fig. 4 Relationship between above-ground biomass and time since abandonment: dashed line = curvilinear regression line based on 71 plots between 3 and 80 years old (Aide *et al.*, 2000); solid line, linear function used in the model for the four successional ages (slope of the line equals sequestration rate, *SR*). Dotted lines represent different scenarios of *SR* used for the sensitivity analysis of higher sequestration rates: 5 Mg ha^{-1} = continuing *SR1524* after 24 years, 3 Mg ha = intermediately high, 1.5 Mg ha^{-1} = continuing with *SR2537* after 37 years. Note that this figure uses the original (Aide *et al.*, 2000) units of Mg of above-ground biomass, whereas in the model these values are transformed into Mg C ha^{-1} and multiplied by 1.4 to account for below-ground carbon (see text for further details).

Model parameterization and calibration

FARMABAND is calculated as the difference in area classified as 'farm' in censuses conducted in 1936, 1940, 1950, 1959, 1964, 1969, 1974, 1978, 1982, 1987, and 1992 (Cruz Baez & Boswell, 1997) divided by the number of years between censuses (i.e. assuming a constant intercensus rate). Running the model with *COEFABAND* = 1 (i.e. assuming that only abandoned farmlands produced forest succession) yielded 275 000 ha of closed-canopy forests in 1992. Using satellite images from 1992, Helmer *et al.* (2002) estimated 364 000 ha of closed-canopy forests. We believe that the difference between these estimates is because abandonment is not a discrete, but a gradual process, and a property classified as a 'farm' can also include areas of young forest. In the model, *COEFABAND* was set at 1.32 to compensate for the difference in the census data and direct observation data. *SR* are derived from above-ground biomass–forest age curves (Aide *et al.*, 2000, Fig. 4) based on chronosequence studies in four study sites within the wet and moist forest life zones (Fig. 1): Luquillo (Aide *et al.*, 1996), Ciales (Rivera & Aide, 1998), Utuado (Marcano-Vega *et al.*, 2002), and Carite (Pascarella *et al.*, 2000). In these studies, secondary forest biomass was calculated from basal area of trees >1 cm of diameter following allometric equations developed for Puerto Rico by Weaver & Guillespe (1992).

In the absence of detailed data of below-ground biomass, the most cost-effective way to estimate soil carbon stocks is to infer them from regression curves with above-ground biomass (Brown, 2002). In Puerto Rico, pastures and agricultural areas have an average soil carbon content (50 cm depth) of approximately 25 Mg C ha^{-1}, and below-ground biomass in 50-year-old secondary forests is approximately 62 Mg C ha^{-1} (Brown & Lugo, 1990; Silver *et al.*, 2000). This implies an increase of 37 Mg C ha^{-1} in the 50 years from the baseline soil carbon level of agricultural lands. This value is 40% of the increase in above-ground biomass for the same period and, thus, to estimate the total biomass *CC* for each successional stage we multiplied above-ground biomass by 1.4. Furthermore, we assumed that when an area is deforested, it maintains the background level of soil carbon regardless of whether it is transformed to an agricultural or urban area and therefore, the background level of soil biomass is not part of any dynamic process in this study. This assumption ignores emissions from top-soil removal during urban construction, but this may be compensated by sequestration in urban parks or gardens, which is not part of the model. When we applied these sequestration rates to the 1990 distribution of forest classes, we estimated an annual net sequestration of 1 467 000 Mg C, which is 23% greater than an estimate based on land-cover categories in 1990 (1 133 800 Mg C, DNER, 1996).

The initial area for *OLD37* in 1936 was 87 500 ha (10% of the island, Grau *et al.*, 2003). The successional forests (*F014*, *F1524*, *F2537*) are assumed to have initial values of zero. The initial value of carbon stock is the product of *CCOLD37* and the initial area of *OLD37*. The area of protected forests (i.e. reserves, 37 000 ha) is based on Helmer *et al.* (2002), and is subtracted from *TOTFOR* in the computation of areas subject to deforestation. *URBAN DENSITY* is the number of people living in urban areas divided by the total area of urban areas. For the period 1977–1994, *URBAN DENSITY* was approximately 20.5 inhabitants ha^{-1} (Cruz Baez & Boswell, 1997; Lopez *et al.*, 2001). The initial value for *URBAN* (19 600 ha) was computed by dividing the 1936 urban population by a density of 20.5 inhabitants ha^{-1}; *P* and *URBAN FRACTION* are based on census data (Cruz Baez & Boswell, 1997).

Per-capita GDP (*PCGDP*) is based on national statistics (Dietz, 1986, http://www.cia.org). Since there is a strong linear relationship between *PCGDP* and per-capita emissions, and Puerto Rico falls very close to the regression line of Neotropical countries (Fig. 2), we assumed a constant value of 0.000236 Mg C dollar^{-1} for *EMGDP*, which is the ratio of emissions and GDP for the year 2000. This is probably an underestimate of the actual past emissions of the island, which could have been higher during the 1960s when the island had a major oil refinery, but is more consistent with our goal of representing emissions due to local consumption.

All area values in the model are in hectares (ha), and carbon budget values in Mg (metric tons) of carbon (Mg C) = 3.6667 Mg CO_2 = 2 Mg biomass. GDP is expressed in US dollars (purchasing parity value). Values of all the parameters are presented in Appendix A.

Model experiments

To describe past trends in carbon sequestration by Puerto Rican ecosystems (Ecosystem Budget Component), we ran the model using the historical values of *FARMABAND*, *URBAN DENSITY*, *POPULATION GROWTH*, and *URBAN FRACTION*. For future scenarios (i.e. 2000–2060), *URBAN FRACTION* is assumed to continue to follow the current trend of linear growth, which implies reaching a value of 1 (i.e. all population living in urban areas) in 2060. Different scenarios of *P*, *URBAN DENSITY*, and *FARMABAND* (Table 1) were used to conduct sensitivity analyses of the effects of these variables on *NETSEQ*. In each run of the sensitivity analysis, one variable changed while the other variables were maintained at a value representative of the most likely scenario given current trends (BAU = 'business as usual'). The BAU scenarios were: (1) *P*, gradual decrease in growth, reaching zero growth in 2080, consistent with global predictions of trends in human population (Lutz *et al.*, 2001), (2) *URBAN DENSITY*, 20.5 people ha^{-1} (1980's values, Cruz Baez & Boswell, 1997; Lopez *et al.*, 2001), and (3) *FARMABAND*, current decreasing trends (Cruz Baez & Boswell, 1997), reaching zero abandonment in 2050. The different scenarios presented for the sensitivity analyses represent increases and decreases in the different variables in relation to the BAU value (Table 1).

Although our model includes sequestration rates based on the best available information, higher sequestration rates may be possible if there is greater sequestration in deeper soil layers (Clark *et al.*, 2001), from an increased frequency of hurricanes and greater input into the soils (Sanford *et al.*, 1991), or through secondary forest management and timber harvesting for the production of long-lasting wood products (Brown *et al.*, 1997). To simulate these scenarios, we conducted a sensitivity analysis with three higher levels of sequestration (Fig. 4): (1) *OLD37* forests continuing at the *F2537* sequestration rate = 1.5. Mg biomass yr^{-1}, (2) continuing sequestration after 25 years (*F2537* and *OLD37*) with a high SR (3 Mg biomass yr^{-1}), and (3) continuing after 25 years with the *F1524* sequestration rate (5 Mg biomass yr^{-1}). Note that in the model, these values are transformed into Mg of carbon, and multiplied by 1.4 to include below-ground biomass (see Model parameterization and calibration section). In the simulations, the original sequestration rates were linearly increased to the new levels between 2000 and 2010. After 2010, the new levels were used in the rest of the simulations.

Table 1 Descriptions of future scenarios beginning in 2000 which vary population growth, urban density, and rates of agricultural land abandonment

Variable and description	Scenarios
P	1.1. Abrupt population decrease to 2.5 million in 2010
Population (inhabitants)	1.2. Steep decrease to zero growth in 2010, stabilizing at 3.75 million
	1.3. Zero growth in 2040, stabilizing at 4.115 million
	1.4. Zero growth in 2080 (BAU)
	1.5. 1990–2000 growth rate (i.e. 5% per decade, 5.1 million in 2060)
URBAN DENSITY	2.1. 10
Urban population density (inhabitants ha^{-1})	2.2. 15
	2.3. 20.5 (BAU)
	2.4. 30
	2.5. 45
	2.6. 60
FARMABAND	3.1. Steep decreasing abandonment (reaching zero abandonment by 2010)
Annual abandonment rate of agricultural lands	3.2. Gradual decrease, reaching zero by 2050 (BAU)
	3.3. 1990's abandonment rate (4500 ha yr^{-1})
	3.4. Early 1980's abandonment rate (10 000 ha yr^{-1})
	3.5. 1965–1969 abandonment rate (maximum registered = 23 800 ha yr^{-1})

BAU, business as usual.

Given that *NETSEQ* was highly sensitive to changes in area of agriculture lands, we simulated the temporal changes in the land-cover component of the model under three scenarios of *FARMABAND* (Scenarios 3.1, 3.2, and 3.5, Table 1). We also conducted a simulation of agricultural expansion (*AGREXPANSION* = 3500 ha yr^{-1} beginning in 2000), which would result in approximately half the agricultural area of 1936 by 2060.

To compare past sequestration with emissions based on GDP, we conducted a sensitivity analysis of carbon emissions during the period 1950–1990 using different *EMGDP* corresponding to other Neotropical countries: very low (0.000056 Mg C dollar^{-1}, Costa Rica), low (0.00013, Dominican Republic), intermediate (0.000236, Puerto Rico), high (0.000265, Cuba, Jamaica), and very high (0.000445, Suriname, Trinidad Tobago).

Presently, to meet the 1990 Kyoto baseline carbon budget, Puerto Rico needs to reduce emissions by approximately 2 million Mg C yr^{-1}. In our model, we varied the values of emissions/GDP (*EMGDP*), population size (*P*), per-capita GDP (*PCGDP*), and rates of farmland abandonment (*FARMABAND*) to determine the impact on the carbon budget in terms of relative Kyoto units (i.e. units of 2 million Mg C). In the *EMGDP* simulations, we used the current values of Cuba–Jamaica, Costa Rica, Dominican Republic, Bahamas (Fig. 2), and the USA (5.5 Mg C/37 000 dollar = 0.00149 Mg C dollar^{-1}). We estimated the reduction in *P* and *PCGDP* that would be required to achieve the Kyoto level by 2010. These emission scenarios were compared with different abandonment scenarios (Scenarios 3.1, 3.3, 3.4, 3.5, Table 1) to determine their relative effects on the island carbon budget.

Results

Our model indicates that net sequestration was slightly negative (i.e. more carbon loss than carbon sequestration) during the period 1936–1950 as urban areas expanded due to population growth and little forest recovery occurred due to low or absent farm abandonment (Fig. 5). After 1950, sequestration rates increased abruptly, and net sequestration became strongly positive, reaching a peak between 1980 and 1990 of approximately 1 500 000 Mg C yr^{-1} (Fig. 5). Although the rates of future sequestration varies with different scenarios of population trends, urban density and abandonment rates, in all cases, sequestration rates after 2040 will be approximately one-third the values of the 1980–1990 period (Fig. 5). If the population growth rate continues at the 1990–2000 level, net sequestration rates will be less than 300 000 Mg C yr^{-1} in 2060 (Fig. 5a). The different scenarios of population stabilization and decrease (Scenarios 1.1–1.4, Table 1) yield sequestration rates between 500 000 and 600 000 Mg C yr^{-1} by 2060. Increasing urban population density in the future will have only minor effects on sequestration rates, while decreases in urban density will produce substantially less sequestration due to an increase in deforestation (Fig. 5b). For example, if future urban population density is reduced to half its current value (Scenario 2.1, Table 1), this will reduce 2010–2060 sequestration rates by 20% compared with values expected from current urban population density. All

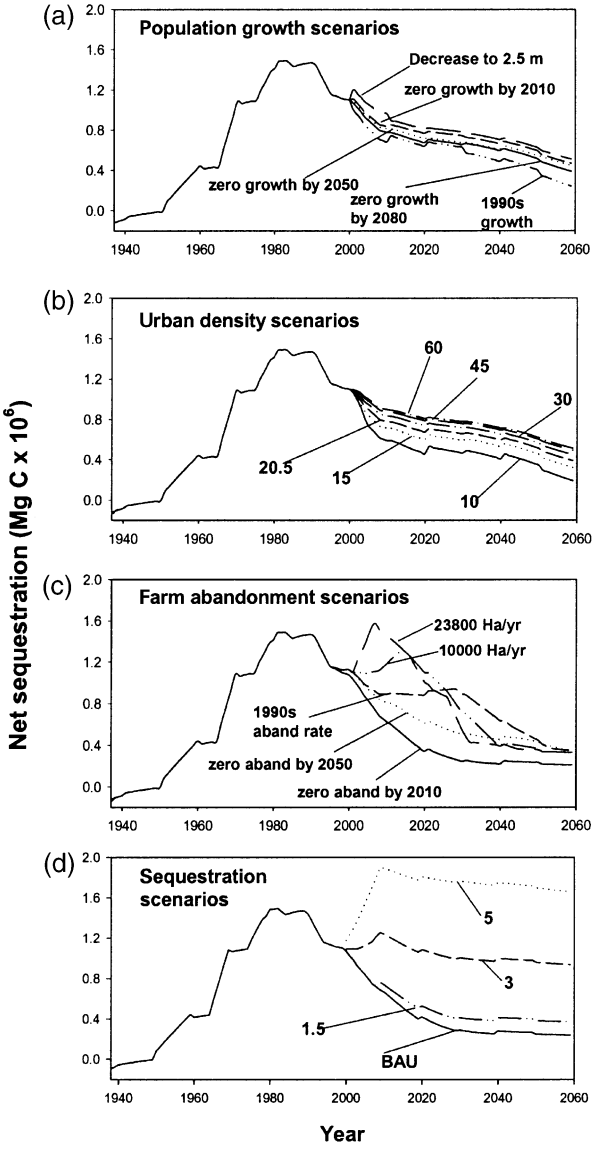

Fig. 5 Net sequestration (*NETSEQ*) time series for the 1936–2000 historical period and under different future scenarios of: (a) Human population (*P*), (b) urban population density (*URBAN DENSITY*), and (c) agricultural abandonment rates (*FARMABAND*), and (d) increasing sequestration rates. For further details on the simulation scenarios, see Table 1 and Fig. 4.

scenarios of farm abandonment will produce approximately the same sequestration rates by 2050 (Fig. 5c); however, they differ strongly in the short term (10–30 years). Increased abandonment can increase sequestration rates to levels as high as in the 1980s by 2010, but high abandonment rates will eliminate remaining agriculture lands quickly, and as there are no new areas for forest succession, sequestration rates will decrease earlier. Sensitivity analysis including higher sequestration rates in old secondary forests (Fig. 5d) show that if the old forests (*OLD37*) continue sequestering carbon at the rate of *F2537*, the effect on *NETSEQ* would be minimal. To maintain high sequestration rates in the future, forests older than 25 years old (*F2537* and *OLD37*) must maintain a rate of at least 50% of the younger forests (*F014*). The only way net sequestration could increase in the future is if forest >25 years maintain an extremely high rate, equivalent to *F1524*.

The area of forests younger than 15 years (*F014*) peaked around 1980 (Fig. 6a) and mid-successional forests (*F014* and *F2537*) were most abundant between 1980 and 2000 (Figs. 6b, c). Old forests decreased slowly until 1980 due to urban growth, but then began to increase as successional forests converted to old forests (Fig. 6d). Between 1990 and 2000, there is a relatively even distribution of area of the different forest ages, and in the future there will be successively more old forests and less early successional forests. The simulations showed that the high abandonment rate scenario (3.5, Table 1) produces an increase in the area of successional forests between 2010 and 2040 (Figs. 6a–c), whereas the agriculture expansion scenario reduces to less than half the area of old forest after 2030 (Fig. 6d).

There was a strong positive correlation between the area of successional forest less than 25 years of abandonment (*YGFOR*, Fig. 7) and *NETSEQ* (Fig. 5). Decreasing abandonment rates will lead towards a reduction in both *YGFOR* (Fig. 7a) and *NETSEQ*, a pattern that will be even more dramatic in the scenario of agricultural expansion (Fig. 7d). The BAU scenario will maintain *YGFOR* for the longest period (Fig. 7b). A scenario of high abandonment rates will produce large areas of *YGFOR* until 2030, but they will later decrease steeply as there will be no more agriculture areas in the island to be abandoned (Fig. 7c). When land abandonment stops, *TOTFOR* shows a slow decreasing trend due to urban expansion, which occurs earlier in the scenario of high *FARMABAND* (Fig. 7c). The scenario of agricultural expansion will produce an early reduction in forests; ending with similar areas of *TOTFOR*, *URBAN*, and *AGRICULTURE* by 2060 (Fig. 7d).

The results of our model demonstrate that during the period 1937–2000 carbon emissions in Puerto Rico were always higher than the sequestration rates (Fig. 8a). Emissions and sequestration were very similar in the late 1950s to early 1960s, but a rapid increase in emissions during the late 1960s was much greater than the increase in sequestration during the same period. During the period 1950–2000, while the ecosystems sequestered a total of 4.6×10^7 Mg C, total emissions were approximately 1.6×10^8 Mg (i.e. 3.5 times higher), and by the year 2000, the annual rate of *EMISSION* was almost nine times higher than *NETSEQ*. In the near future, *NETSEQ* is expected to decrease, and current trends in *GDP* and *P* indicate a continued increase in *EMISSION* unless consumption patterns or technology change substantially.

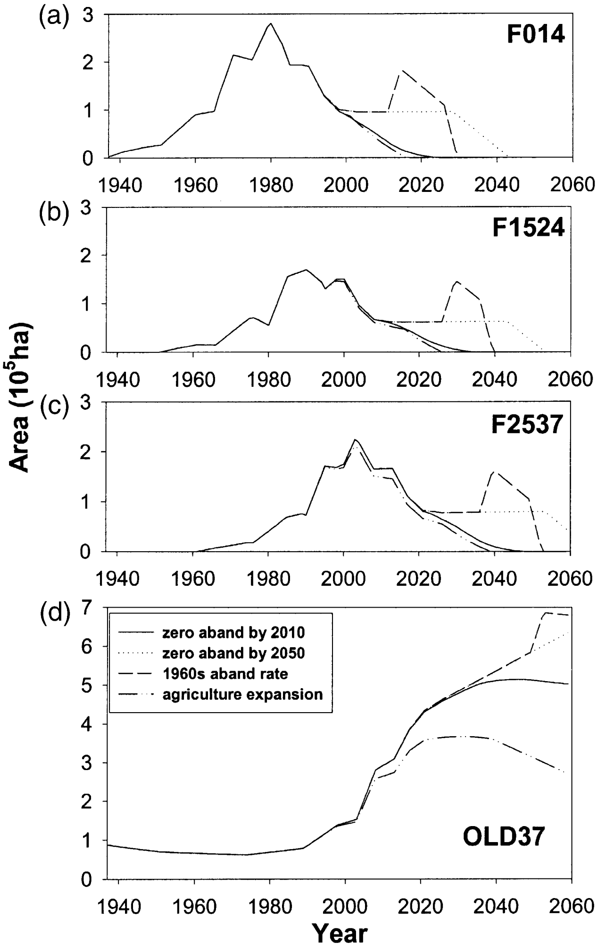

Fig. 6 (a–d) Temporal changes in cover of different forest types (defined by successional age and sequestration rates, Fig. 4) from 1936 to 2060 for three scenarios of land abandonment rate and one scenario of agriculture expansion beginning in 2000. For further details on the simulation scenarios see Table 1.

The sensitivity analysis indicates that *EMISSION* is highly dependent on *EMGDP* (emissions/GDP ratio). For example, if Puerto Rico had an *EMGDP* equivalent to the Dominican Republic, its *NETSEQ* would have compensated for the carbon emissions of the 1970s, and

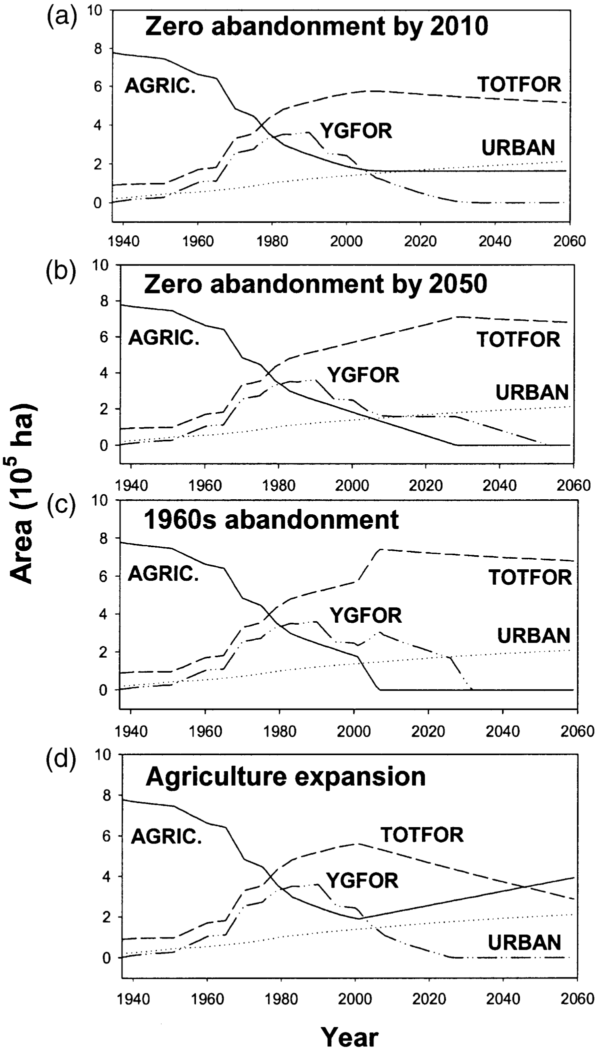

Fig. 7 Changes in the area of agriculture lands, total forest, young forests (i.e. less than 25 years old), and urban areas under different scenarios of land use. For further details on the simulation scenarios, see Table 1.

an *EMGDP* equivalent to Costa Rica, emissions would have been compensated by sequestration until 1990 (Fig. 8b). The relative importance of the emission–GDP ratio is also evident for future emission scenarios (Fig. 8c). For example, to return to the level of emission in 1990 (i.e. Kyoto Protocol compliance) and to maintain the current *EMGDP* of Puerto Rico it would be necessary to reduce GDP by $2530 per capita or reduce the population by 891 000 inhabitants (24% of the 2000 population). If the *EMGDP* of Puerto Rico was reduced to a level similar to Costa Rica, the Dominican Republic, or the Bahamas, emissions would be lower than in 1990, and reaching an *EMGDP* comparable with the USA would yield emission reductions almost to the 1990s level. In contrast, emissions would increase if *EMGDP* is

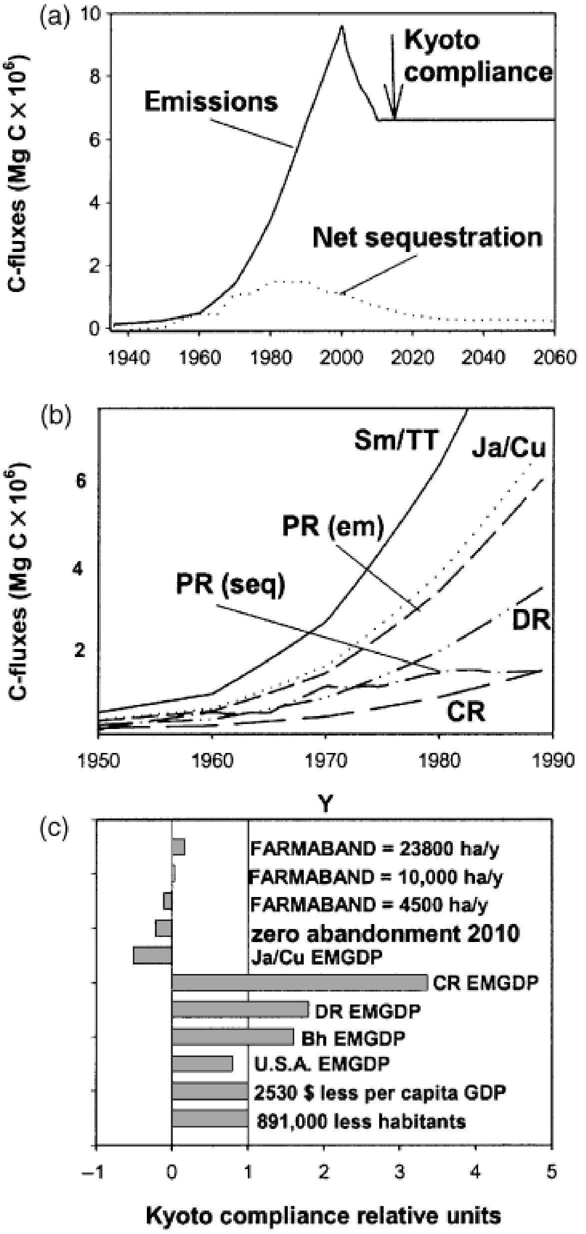

Fig. 8 Emission trends and scenarios in Puerto Rico: (a) Comparison of emissions and net sequestration. Future emissions assume a reduction by 2010–1990 levels (Kyoto baseline). (b) Sensitivity analysis of 1950–1990 emissions using *EMGDP* values of countries with different emission/gross domestic product (GDP) ratios (Fig. 2). Net sequestration of Puerto Rico is also plotted for comparative purposes. (c) Effect on carbon budget of changes in different variables, relative to the changes in carbon balance required to achieve 1990's (Kyoto baseline) emissions by 2010. Negative values indicate a more negative carbon balance, and positive values indicate a less negative carbon balance. A Kyoto compliance unit of 1 equals 2 million Mg C, the approximate amount that Puerto Rico needs to reduce to reach the 1990 emission level.

similar to the current values of either Cuba or Jamaica. Changes in abandonment rate are expected to produce changes in the carbon balance of much less magnitude than the changes that can be expected from changes in emissions. For example, the scenario of agriculture abandonment that produces the highest sequestration rate would be equivalent to less than 20% the reduction in emissions required to reach the 1990s level (Fig. 8c).

Discussion

Sequestration rates in Puerto Rico reached a peak during the 1980s, and are likely to decline to less than 50% of the peak values as forests mature (Fig. 5). The peak in sequestration occurred approximately 30–40 years after the initiation of the socioeconomic shift from agriculture to industry (Dietz, 1986), due to the increase in young secondary forest, with high sequestration rates, on abandoned agricultural lands. To maintain these high levels of sequestration, the rate of farm abandonment would have to continue at its present level, but this is highly unlikely. First, most agricultural land has already been abandoned, and secondly, future abandonment will probably be restricted to the remaining areas of small-scale agriculture while areas of more profitable intensive agriculture are likely to persist in the landscape. Although management practices aiming to harvest long-lasting wood products may increase long-term forest sequestration, there is no prospect of such activity at a significant scale in Puerto Rico. Several plantations have been established across Puerto Rico, and these areas often have high sequestration rates (Lugo, 1992). Approximately 6000 ha of plantations occur on the island (Wadworth, 1997), but given that this represents less than 0.7% of the total area of Puerto Rico, they will have a negligible impact on the carbon budget.

The recovery of secondary forests in Puerto Rico has been responsible for the dramatic increase in carbon sequestration during the last 50 years. Presently, there is a relatively even mix of different aged forests (Fig. 6). This is a unique and transient situation because in the past, early successional forests dominated the island, and most future scenarios indicate that old forests will dominate net sequestration after 2040. The rapid recovery of forest in Puerto Rico was facilitated by small farm sizes and the infrequent use of fire for pasture management (Grau *et al.*, 2003). In other tropical areas, the frequent use of fire, soil degradation, or long distances to seed sources (e.g. Cavelier *et al.*, 1998; Janzen, 1998; Nepstad *et al.*, 2001) will result in slower rates of forest recovery.

Frequent severe hurricane disturbances also distinguish Puerto Rico (approximately once every 50 years; Scatena & Larsen, 1991) from many other tropical areas. Except in the most severe cases, strong hurricanes transfer forest biomass from the canopy to the forest floor without causing substantial tree mortality (Lugo & Scatena, 1996); therefore, the impacts of hurricanes on forest succession are limited (Zimmerman *et al.*, 1994). The potential effects of hurricanes on carbon balance are not well known. In the short term, hurricanes cause a transient increase in forest productivity (Scatena *et al.*, 1996) at the same time carbon from decomposing hurricane debris is lost to the atmosphere (Vogt *et al.*, 1996). Although a decomposition–production model (CENTURY; Sanford *et al.*, 1991) suggested that hurricane disturbance should, in the long-term, cause increased levels of soil carbon (i.e. sequestration), field measurements detected no effect of a single hurricane on soil carbon levels (Silver *et al.*, 1996). Thus, the effects of hurricanes on the carbon budget of Puerto Rico are poorly resolved, but probably largely transient and, to a degree, self-balancing. For these reasons, hurricane effects on the carbon budget of Puerto Rico were omitted from the modeling efforts presented here.

Although urban areas have expanded rapidly during the last 60 years in Puerto Rico (Thomlinson *et al.*, 1996; Lopez *et al.*, 2001), the effect on carbon budget has been comparatively minor, because most development has been on agricultural land (Lopez *et al.*, 2001) and at relatively high urban population densities. Recently, this pattern has begun to shift as more low-density urban areas are being developed in montane areas (Thomlinson & Rivera, 2000). If this trend continues, these urban areas could have a significant impact on the carbon budget. In our model, the proportion of the total area deforested is applied to all forest classes (i.e. assuming that deforestation, mainly due to urban expansion, is not biased towards particular forest successional ages). Consistent with this assumption, the best predictor of the location of urban expansion in the Luquillo municipality was the relative area of each land-cover type (Thomlinson *et al.*, 1996; Thomlinson & Rivera, 2000). Although accessibility is a good predictor of urban expansion at the island-wide scale (Grau *et al.*, 2003), given that 99.4% of the island area is located within 1 km of the nearest road, all forest types should be similarly accessible.

Another important factor that could affect the impact of urban areas on the carbon budget is population growth. Although the population of Puerto Rico increased from 1 to >3.7 million during the 20th century, the growth rate has dropped dramatically during the last two decades (Cruz Baez & Boswell, 1997). The political status of Puerto Rico, and variation in migration rates, emigration of Puerto Ricans to the United States (Boswell, 1985; Rivera-Batis & Santiago, 1995) and immigration from other Caribbean countries, particularly the Dominican Republic (Cruz Baez & Boswell, 1997), may be the most important factors affecting changes in forest areas due to urban development.

Additionally, significant carbon losses and a decrease in net sequestration rates could occur if there was an increase in agriculture areas (Fig. 6d). Although there are a few examples of economies that have shifted from industry to agriculture, if the status of Puerto Rico changed to an independent country, this could result in an increase in agricultural activities similar to those of other countries in the region.

Despite the rapid recovery of secondary forests in Puerto Rico (Thomlinson *et al.*, 1996; Aide *et al.*, 2000; Grau *et al.*, 2003) and their high sequestration rates, the carbon budget of the island is negative (Fig. 8a), because ecosystem sequestration rates are low in comparison with emissions from the use of fossil fuel. Although forest recovery in Puerto Rico contrasts with the dominant trend of deforestation in the tropics (Turner *et al.*, 1990; Houghton, 1999; Fearnside, 2000) the socioeconomic drivers that promoted reforestation also increased industrialization and urbanization (Dietz, 1986; Lopez *et al.*, 2001) resulting in a dramatic increase in per-capita energy consumption and carbon emissions, with ratios between emission and GDP which are even higher than in the USA. In other countries, where population densities are low, an increase in emissions due to an increase in GDP may be temporarily balanced by sequestration in secondary forests (Fig. 8b). For example, if land abandonment is associated with agricultural intensification on more productive lands (Northeastern Brazil, Moran *et al.*, 1996) or if there is a shift toward moderate levels of industrialization (Dominican Republic, Zweifler *et al.*, 1994), emission/GDP ratio may be lower and sequestration may balance emissions for longer times.

The major limitations of our model are the assumption of ecological homogeneity throughout the island and the lack of detailed soil carbon dynamics. Although the dry forest zone may have lower sequestration rates in comparison with the data, we have used from moist and wet forest, our island-wide estimates of carbon sequestration are similar to the government estimate for 1990 (DNER, 1996). Given that the dry forest life zone contains the prime agricultural areas, changes in land use have been less dynamic in this life zone in comparison with the moist and wet zones. Although coastal wetland forests have high carbon content, they were not analyzed separately. The conversion of these forests to agriculture mainly occurred during the 19th century and beginning of the 20th century. During the period modeled in this study there has been little change in the distribution of this forest type. Holdridge (1940) estimated 6475 ha of mangroves for 1938, and Helmer *et al* (2002) estimated 6838 ha for the land-cover category, tidally semipermanently flooded evergreen screlophylous forest. Future urban development in areas of coastal wetlands would increase carbon emissions, but given that they cover only 0.7 % of the island (Helmer *et al.*, 2002), these changes would have a very minor effect on island-wide estimates. As in many other studies of carbon budgets, soil carbon data are limited. Ongoing studies will help refine our model estimates, but until soils studies begin to document soil carbon beyond depths of 10–100 cm, we will continue to underestimate the contribution of this component (Clark *et al.*, 2001; Murty *et al.*, 2002).

Despite these limitations, the availability of replicated data of above-ground biomass along chronosequences and the description of land-use change dynamics during the last 60 years have allowed us to estimate the carbon balance for a long period in a tropical country, and to make predictions of carbon budget for the future given current socioeconomic trends.

Conclusions

(1) Sequestration rates peaked 30–40 years after socioeconomic changes in the 1950s which lead to agricultural abandonment and forest regeneration. After approximately 100 years, net ecosystem sequestration will be less than 50% of the peak rates due to the dominance of mature forests with lower sequestration rates. Although this time period will be longer in temperate ecosystems and other tropical ecosystems with different disturbance regimes, these results demonstrate the limitations of forests as a long-term ($>$100 years) solution for reducing atmospheric CO_2.

(2) If high sequestration rates in secondary forests on abandoned agricultural lands are coupled with a new economy with a high emission/GDP ratio, as in Puerto Rico, even the highest sequestration rates will be exceeded by emission rates, leading to a strongly negative carbon budget. Increasing forest cover will only be able to balance carbon budgets if a country has low emission energy sources (e.g. hydroelectric – Costa Rica) or population densities much lower than Puerto Rico (e.g. Tropical Andes).

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Appendix A. STELLA program codes for the model of Puerto Rico Carbon Budget

```
AGRICULTURE(t) = AGRICULTURE(t - dt) + (AGREXPANSION -
ABANDONMENT) * dt
INIT AGRICULTURE = 780000
INFLOWS:
AGREXPANSION = 0
OUTFLOWS:
ABANDONMENT = FARMABAND*COEFABAND

CARBON_STOCK(t) = CARBON_STOCK(t - dt) + (SEQUESTRATION - LOSS) * dt
INIT CARBON_STOCK = CCOLD_37*OLD37
INFLOWS:
SEQUESTRATION = F014*SR014+F1524*SR1524+F2537*SR2537+OLD37*SR0LD
OUTFLOWS:
LOSS =(DEF014*CC014)+(CC1524*DEF1524)+(DEF2537*CC2537)+(DEFOLD*CCOLD37)


EMITTED(t) = EMITTED(t - dt) + (EMISSION) * dt
INIT EMITTED = 0
INFLOWS:
EMISSION = P*PCEMIS

F014(t) = F014(t - dt) + (ABANDONMENT - tr15 - DEF014) * dt
INIT F014 = 0
          TRANSIT TIME = 15
          INFLOW LIMIT = INF
          CAPACITY = INF
INFLOWS:
ABANDONMENT = FARMABAND*COEFABAND
OUTFLOWS:
tr15 = CONVEYOR OUTFLOW
DEF014 = LEAKAGE OUTFLOW
          LEAKAGE FRACTION = 14*DEFRATE/(TOTFOR-37000)
          NO-LEAK ZONE = 0

F1524(t) = F1524(t - dt) + (tr15 - tr25 - DEF1524) * dt
INIT F1524 = 0
          TRANSIT TIME = 10
          INFLOW LIMIT = INF
          CAPACITY = INF
INFLOWS:
tr15 = CONVEYOR OUTFLOW
OUTFLOWS:
tr25 = CONVEYOR OUTFLOW
DEF1524 = LEAKAGE OUTFLOW
```

```
        LEAKAGE FRACTION = 9*DEFRATE/(TOTFOR-37000)
        NO-LEAK ZONE = 0

F2537(t) = F2537(t - dt) + (tr25 - tr37 - DEF2537) * dt
INIT F2537 = 0
        TRANSIT TIME = 13
        INFLOW LIMIT = INF
        CAPACITY = INF
INFLOWS:
tr25 = CONVEYOR OUTFLOW
OUTFLOWS:
tr37 = CONVEYOR OUTFLOW
DEF2537 = LEAKAGE OUTFLOW
        LEAKAGE FRACTION = 12*DEFRATE/(TOTFOR-37000)
        NO-LEAK ZONE = 0

OLD37(t) = OLD37(t - dt) + (tr37 - DEFOLD) * dt
INIT OLD37 = 87500
INFLOWS:
tr37 = CONVEYOR OUTFLOW
OUTFLOWS:
DEFOLD = DEFRATE*(OLD37-37000)/(TOTFOR-37000)

URBAN(t) = URBAN(t - dt) + (URBAN_GROWTH) * dt
INIT URBAN = 19500
INFLOWS:
URBAN_GROWTH = (1/URBAN_DENSITY)*DERIVN(URBAN_POP,1)/DT

CARBON_BALANCE = NETSEQ-EMISSION
CC014 = 70*.5
CC1524 = 175*.5
CC2537 = 224*.5
CCFOR = TOTFOR-F014
CCOLD_37 = 266*.5
COEFABAND = 1.32
DEFRATE = URBAN_GROWTH+AGREXPANSION
EMGDP = 0.000236
LTBALANCE = CARBON_STOCK-EMITTED
NETSEQ = (SEQUESTRATION-LOSS)
PCEMIS = EMGDP*PCGDP
SR014 = 6.66*1.4*.5
SR0LD = 1*1.4*.5
SR1524 = 5*1.4*.5
SR2537 = 1.5*1.4*.5
TOTFOR = F014+F1524+F2537+OLD37
URBAN_DENSITY = 20.5
```

URBAN_POP = P*URBAN_FRACTION
YGFOR = F014+F1524

FARMABAND = GRAPH(TIME)
(1936, 2100), (1937, 2100), (1938, 2100), (1939, 2100), (1940, 2100), (1941, 1575), (1942, 1575), (1943, 1575), (1944, 1575), (1945, 1575), (1946, 1575), (1947, 1575), (1948, 1575), (1949, 1575), (1950, 1575), (1951, 7000), (1952, 7000), (1953, 7000), (1954, 7000), (1955, 7000), (1956, 7000), (1957, 7000), (1958, 7000), (1959, 7000), (1960, 3150), (1961, 3150), (1962, 3150), (1963, 3150), (1964, 3150), (1965, 23800), (1966, 23800), (1967, 23800), (1968, 23800), (1969, 23800), (1970, 5775), (1971, 5775), (1972, 5775), (1973, 5775), (1974, 5775), (1975, 17063), (1976, 17063), (1977, 17063), (1978, 17063), (1979, 10938), (1980, 10938), (1981, 10938), (1982, 10938), (1983, 5775), (1984, 5775), (1985, 5775), (1986, 5775), (1987, 5775), (1988, 4900), (1989, 4900), (1990, 4900), (1991, 4900), (1992, 4900), (1993, 5000), (1994, 4500), (1995, 4250), (1996, 4250), (1997, 4125), (1998, 3875), (1999, 3750), (2000, 3750), (2001, 3125), (2002, 2875), (2003, 2625), (2004, 2250), (2005, 1750), (2006, 1125), (2007, 875), (2008, 625), (2009, 500), (2010, 0.00), (2011, 0.00), (2012, 0.00), (2013, 0.00), (2014, 0.00), (2015, 0.00), (2016, 0.00), (2017, 0.00), (2018, 0.00), (2019, 0.00), (2020, 0.00), (2021, 0.00), (2022, 0.00), (2023, 0.00), (2024, 0.00), (2025, 0.00), (2026, 0.00), (2027, 0.00), (2028, 0.00), (2029, 0.00), (2030, 0.00), (2031, 0.00), (2032, 0.00), (2033, 0.00), (2034, 0.00), (2035, 0.00), (2036, 0.00), (2037, 0.00), (2038, 0.00), (2039, 0.00), (2040, 0.00), (2041, 0.00), (2042, 0.00), (2043, 0.00), (2044, 0.00), (2045, 0.00), (2046, 0.00), (2047, 0.00), (2048, 0.00), (2049, 0.00), (2050, 0.00), (2051, 0.00), (2052, 0.00), (2053, 0.00), (2054, 0.00), (2055, 0.00), (2056, 0.00), (2057, 0.00), (2058, 0.00), (2059, 0.00), (2060, 0.00), (2061, 0.00), (2062, 0.00), (2063, 0.00), (2064, 0.00), (2065, 0.00), (2066, 0.00), (2067, 0.00), (2068, 0.00), (2069, 0.00), (2070, 0.00), (2071, 0.00), (2072, 0.00), (2073, 0.00), (2074, 0.00), (2075, 0.00), (2076, 0.00), (2077, 0.00), (2078, 0.00), (2079, 0.00), (2080, 0.00)

P = GRAPH(TIME)
(1930, 1.5e+006), (1940, 1.9e+006), (1950, 2.2e+006), (1960, 2.4e+006), (1970, 2.7e+006), (1980, 3.2e+006), (1990, 3.5e+006), (2000, 3.7e+006), (2010, 3.9e+006), (2020, 4e+006), (2030, 4.2e+006), (2040, 4.2e+006), (2050, 4.3e+006), (2060, 4.4e+006), (2070, 4.4e+006)

PCGDP = GRAPH(TIME)
(1920, 0.00), (1930, 250), (1940, 320), (1950, 451), (1960, 859), (1970, 2224), (1980, 4592), (1990, 7900), (2000, 11000), (2010, 13200), (2020, 15400), (2030, 17600), (2040, 19800), (2050, 22000), (2060, 24200), (2070, 26400), (2080, 28600)

URBAN_FRACTION = GRAPH(TIME)
(1930, 0.15), (1940, 0.285), (1950, 0.405), (1960, 0.48), (1970, 0.565), (1980, 0.665), (1990, 0.725), (2000, 0.775),