Supplementary materials of manuscript "Gross primary productivity of forest ecosystems in a subtropical city and its decadal climatic and environmental drivers" authored by Lam, H. C. H., Yung, D. H. Y., Tao, D. K. C., Lo, J. T. W., Wong, M. S., Wu, J., and Tai, A. P. K..

Methods S1 TEMIR-HK model schemes that are closely relevant for this study, extracted from Tai et al. (2024).

1. Canopy radiative transfer

Each PFT simulated per vegetated grid cell is represented as a single "big-leaf" canopy of sunlit and shaded leaves. In brief, the absorbed PAR averaged over the sunlit and shaded canopy per unit plant area (leaf plus stem area) is

$$\phi_{\mathrm{sun}} = \frac{f_{\mathrm{sun,dir}} I_{\mathrm{dir}} + f_{\mathrm{sun,diff}} I_{\mathrm{diff}}}{\mathrm{PAI_{sun}}} \tag{1}$$

$$\phi_{\mathrm{sha}} = \frac{f_{\mathrm{sha,dir}} I_{\mathrm{dir}} + f_{\mathrm{sha,diff}} I_{\mathrm{diff}}}{\mathrm{PAI_{sha}}} \tag{2}$$

where $f_{\mathrm{sun/sha,dir/diff}}$ is the fraction of direct/diffuse incident radiation absorbed by the sunlit/shaded leaves and stems as calculated by the two-stream approach; the sunlit and shaded plant area index (PAI = LAI + SAI) is

$$\mathrm{PAI_{sun}} = \frac{1 - e^{-K_b(\mathrm{LAI+SAI})}}{K_b} \tag{3}$$

$$\mathrm{PAI_{sha}} = (\mathrm{LAI} + \mathrm{SAI}) - \mathrm{PAI_{sun}} \tag{4}$$

and K_b is calculated following the two-stream approximation. The sunlit and shaded LAI ultimately used to calculate canopy photosynthesis are

$$\mathrm{LAI_{sun}} = \mathrm{PAI_{sun}} \frac{\mathrm{LAI}}{\mathrm{LAI+SAI}} \tag{5}$$

$$\mathrm{LAI_{sha}} = \mathrm{PAI_{sha}} \frac{\mathrm{LAI}}{\mathrm{LAI+SAI}} \tag{6}$$

2. Canopy photosynthesis and conductance

Leaf photosynthesis of both C3 and C4 plants is represented by the well-established formulation that relates to Michaelis–Menten enzyme kinetics and photosynthetic biochemical pathways (Farquhar et al., 1980; Von Caemmerer and Farquhar, 1981; Collatz et al., 1991; Collatz et al., 1992), which considers three limiting regimes:

(i) The Rubisco-limited photosynthesis rate (A_c, μmol CO_2 m^{-2} s^{-1}) captures the rate of carbon assimilation when substrate availability or enzyme activity is the limiting factor:

$$\boldsymbol{A_c} = \begin{cases} \boldsymbol{V_{\mathrm{cmax}}} \dfrac{c_i - \Gamma_*}{c_i + K_c * \left(1 + \frac{o_i}{K_o}\right)} & \textbf{for C3 plants} \\ \boldsymbol{V_{\mathrm{cmax}}} & \textbf{for C4 plants} \end{cases} \tag{7}$$

where c_i (Pa) the intercellular CO_2 partial pressure; K_c and K_o are the Michaelis–Menten constants for carboxylation and oxygenation (Pa), respectively; o_i (Pa) is the intercellular oxygen partial pressure; Γ_* (Pa) is the CO_2 compensation point and V_{cmax} (μmol CO_2 m^{-2} s^{-1}) is the maximum rate of carboxylation.

(ii) The RuBP-limited photosynthetic rate (A_j, μmol CO_2 m^{-2} s^{-1}) defines the photosynthesis rate as light intensity and thus RuBP regeneration are the limiting factor:

$$A_j = \begin{cases} \frac{J}{4}\left(\frac{c_i - \Gamma_*}{c_i + 2\Gamma_*}\right) & \text{for C3 plants} \\ 0.23\phi & \text{for C4 plants} \end{cases} \tag{8}$$

where J (μmol m^{-2} s^{-1}) is the electron transport rate, and ϕ (W m^{-2}) is the absorbed PAR for either sunlit (ϕ_{sun}) or shaded (ϕ_{sha}) leaves as calculated by the canopy radiative transfer model. For C_3 plants, J is determined by ϕ as well, and is determined as the smaller of the two roots of the quadratic equation:

$$\Theta_{PSII} J^2 - (I_{PSII} + J_{max}) J + I_{PSII} J_{max} = 0 \tag{9}$$

where J_{max} (μmol m^{-2} s^{-1}) is the maximum potential rate of electron transport; $\Theta = 0.7$ is the curvature parameter; I_{PSII} (μmol m^{-2} s^{-1}) is the light utilized in electron transport by photosystem II, determined by:

$$I_{PSII} = 2.3\Phi_{PSII}\,\phi \tag{10}$$

where $\Phi_{PSII} = 0.85$ is the quantum yield of photosystem II.

(iii) The product-limited photosynthetic rate (A_p, μmol CO_2 m^{-2} s^{-1}) represents the limitation from the regeneration rate of photosynthetic phosphate compounds:

$$A_p = \begin{cases} 3\,T_p & \text{for C3 plants} \\ k_p \frac{c_i}{P_{atm}} & \text{for C4 plants} \end{cases} \tag{11}$$

where T_p is the triose phosphate utilization rate (μmol m^{-2} s^{-1}), P_{atm} (Pa) is the ambient atmospheric pressure, and k_p is the initial slope of CO_2 response curve for C4 plants. The model considers colimitation (Collatz et al., 1991; Collatz et al., 1992), and the leaf-level gross photosynthesis rate (A, μmol CO_2 m^{-2} s^{-1}) is given by the smaller root of the equations:

$$\Theta_{cj} A_i^2 - (A_c + A_j)A_i + A_c A_j = 0 \tag{12}$$

$$\Theta_{ip} A^2 - (A_i + A_p)A + A_i A_p = 0$$

The net photosynthesis rate (A_n, μmol CO_2 m^{-2} s^{-1}) is then:

$$A_n = A - R_d \tag{13}$$

$$R_d = \begin{cases} 0.015\, V_{cmax} \frac{f_{R_d}(T_v)}{f_{V_{cmax}}(T_v)} & \text{for C3 plants} \\ 0.025\, V_{cmax} \left(\frac{(1 + \exp[s_1(T_v - s_2)])(1 + \exp[s_3(T_v - s_4)])}{1 + \exp[s_5(T_v - s_6)]}\right) & \text{for C4 plants} \end{cases}$$

where R_d (μmol CO_2 m^{-2} s^{-1}) is the dark respiration rate; s_1, s_3 and s_5 are 0.3, 0.2 and 1.3 K, respectively; s_2, s_4, and s_6 and 313.15, 288.15, and 328.15 K^{-1}, respectively; T_v is leaf temperature (K); and $f_{R_d}(T_v)$ and $f_{V_{cmax}}(T_v)$ are functions to adjust for variations due to temperature (Bonan et al., 2011). All of the parameters (V_{cmax}, J_{max}, T_p, R_d, K_c, K_o, Γ_*, k_p) are temperature-dependent and scale with their respective PFT-specific standard values at 25°C by different formulations. Temperature acclimation of V_{cmax} and J_{max} from the previous 10 days as well as daylength dependence of V_{cmax} is implemented as default options. These are all detailed in Sect. 8.2 and 8.3 of Oleson et al. (2013).

3. Ozone damage

Two ozone (O_3) damage schemes are implemented in TEMIR, which considers the responses of vegetation in terms of photosynthesis and stomatal conductance. In this study we used the first O_3 damage scheme following Sitch et al. (2007) and considers two levels of O_3 sensitivity (high and low) for each of the five major plant groups, namely, "broadleaf", "needleleaf", "shrub", "C3 grass", "C4 grass" as defined by Karlsson et al. (2004) and Pleijel et al. (2004). These groups are mapped to the default TEMIR PFTs accordingly. The scheme represents O_3 damage by an O_3 impact factor (f) that is dependent on the instantaneous stomatal O_3 flux into the leaf interior:

$$f = 1 - a \max\left[\left(\frac{[O_3]}{g_{ah}^{-1} + g_b^{-1} + k_{O_3} g_s^{-1}} - F_{crit}\right), 0\right] \tag{14}$$

where $[O_3]$ (nmol m^{-3}) is the O_3 concentration observed or of the lowest atmospheric model layer; the aerodynamic, leaf boundary layer and stomatal conductances are calculated using the formulations in the previous sections; $k_{O3} = 1.67$ as defined by Sitch et al. (2007) is the ratio of the leaf resistance for O_3 to that for water vapor; F_{crit} represents a critical threshold accounting for O_3 tolerance, below which instantaneous O_3 exposure does not affect photosynthesis, and $F_{crit} = 1.6$ nmol m^{-2} s^{-1} for woody PFTs and $F_{crit} = 5$ nmol m^{-2} s^{-1} for grass PFTs; the O_3 sensitivity parameter a ($nmol^{-1}$ m^2 s) is specific to the plant group and to the two levels of O_3 sensitivity. Factor f is multiplied directly to the net photosynthesis rate A_n to represent O_3 damage, which then indirectly affects g_s via the coupling between A_n and g_s; since the calculation of f requires g_s, the three variables f, A_n and g_s need to be solved together by numerical iterations.

Table S1 Land cover type to plant functional type cross-walking table with 24 level 2 FROM-GLC classes that are abundant in Hong Kong. The unit of the values is the percentage coverage of each PFT per unit land area. The row sum of the percentage does not necessarily equal 1. The abbreviations are referred as follow: BETT: broadleaf evergreen tropical tree; BDTT: broadleaf deciduous tropical tree; NETT: needleleaf evergreen temperate tree; BES: broadleaf evergreen shrub; BDTS: broadleaf deciduous temperate shrub; C3 G: C3 grass.

FROM-GLC		Tree			Shrub		Grass	Non-vegetated
Class	Class code	BETT	BDTT	NETT	BES	BDTS	C3 G	Bareland
Rice paddy	11	15			10		15	
Greenhouse	12	15			10		15	
Other farmland	13	15			10		15	
Orchard	14	15			10		15	
Bare farmland	15				20		30	50
Broadleaf leaf-on	21	70			30			
Broadleaf leaf-off	22	70			30			
Needleleaf leaf-on	23			70	10	5	15	
Needleleaf leaf-off	24			70	10	5	15	
Mixed leaf type leaf-on	25	30	30		30		10	
Mixed leaf type leaf-off	26	30	30		30		10	
Pasture leaf-on	31				10		90	
Natural grassland leaf-on	32				10		90	
Grassland leaf-off	33				10		90	
Shrub cover leaf-on	41				100			
Shrub cover leaf-off	42				100			
Marshland leaf-on	51				10		90	
Mudflat	52						50	50
Marshland leaf-off	53				10		90	
Water	60							
Shrub and brush tundra	71				15		35	50
Herbaceous tundra	72				15		35	50
Impervious	80							
Barren land	90							100

Table S2 Statistical parameters of linear regression and non-parametric Mann-Kendall trend test (M-K test) of yearly total GPP from all factorial simulations and MODIS GPP.

Case/Statistics	**Trend (TgC year^{-2})**	**Trend (gC m^{-2} year^{-2})**	***R^2***	***p*-value (M-K test)**
⟨Full⟩	0.01286	115.4	0.8029	0.00025
⟨CO2_fixed⟩	0.00738	66.21	0.5663	0.00410
⟨Temp_fixed⟩	0.00464	41.63	0.5282	0.00410
⟨O3_fixed⟩	0.01150	103.2	0.7963	0.00011
⟨LAI_fixed⟩	0.01340	120.2	0.7977	0.00017
MODIS	0.01145	102.8	0.5655	0.00410

Figure S1 Temporal evolution of leaf area index (LAI) in Hong Kong adopted from MODIS MCD15A3H v006 4-days composite LAI data product with 500-m resolution. (a) Mean LAI between 2004–2008. (b, c) Absolute change in LAI (m^2 m^{-2}) with respect to (a) from the mean between (b) 2009–2013 and (c) 2014–2018. (d-e) Percentage change in LAI (%) with respect to (a) from the mean between (d) 2009–2013 and (e) 2014–2018.

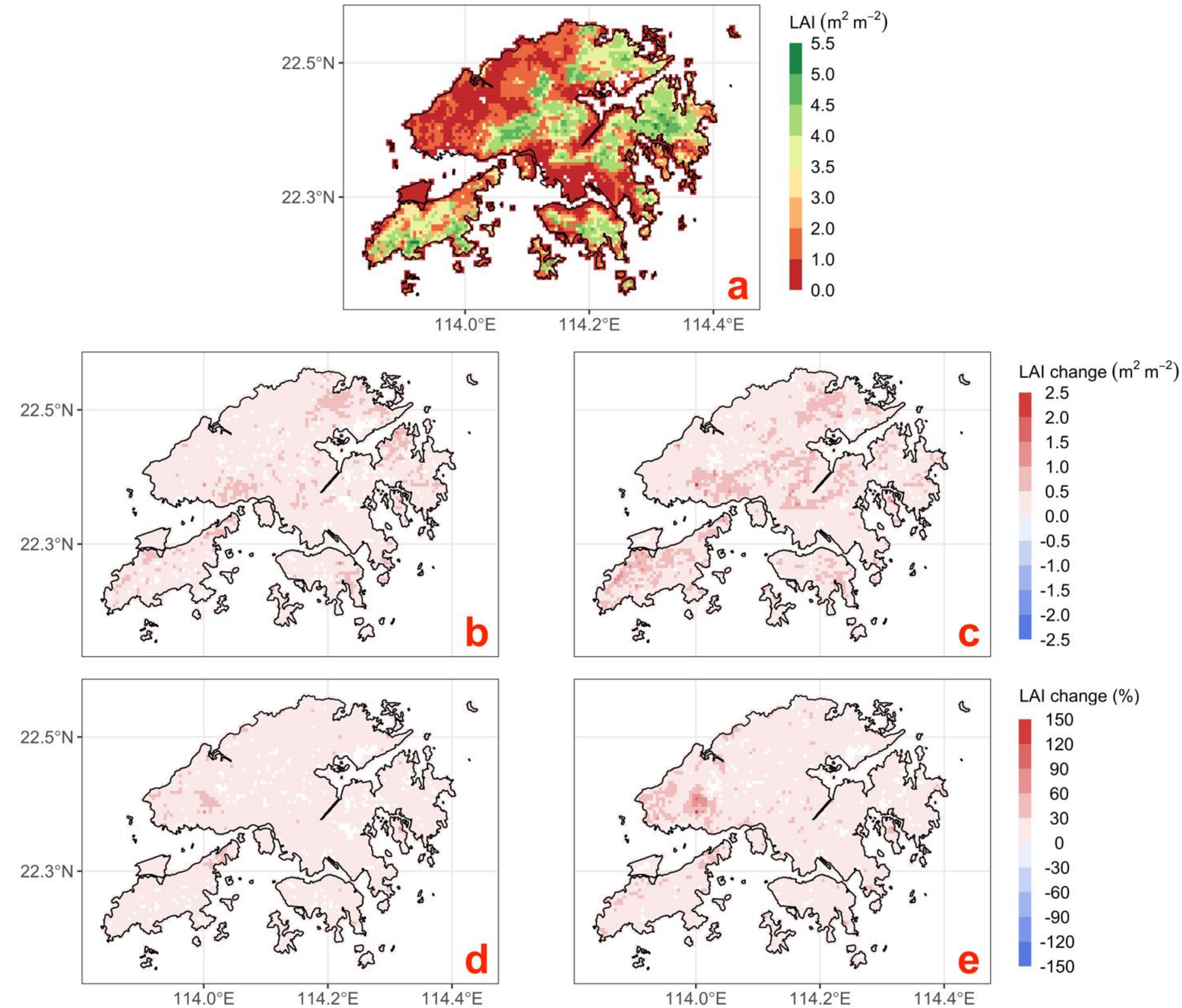

Figure S2 Spatial pattern of mean gross primary productivity (GPP) standard deviation (SD) of Hong Kong from (a) observed MOD17A2HGFv6.1 product and (b) simulated Terrestrial Ecosystem Model in R (TEMIR–HK) for 2004–2018. (c) Spatial correlation between the observed and simulated GPP SD. Red solid line indicates the linear regression line, blue dashed line indicates 1:1 line. The coloured contours show the density of the points. The statistical metrics and the equation of the linear regression are annotated at the top-left corner of the plot.

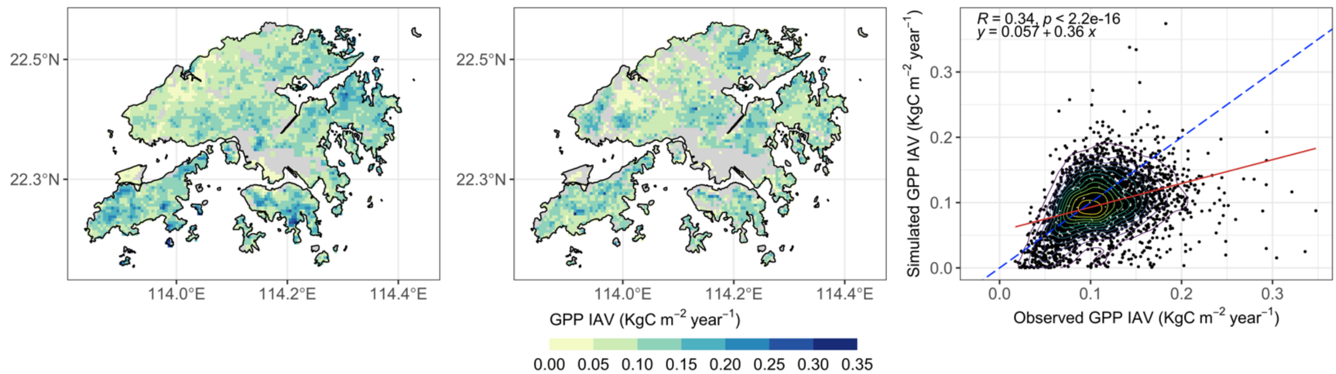

Figure S3 Monthly time series of leaf area index (LAI) in Hong Kong. Each coloured line represents a 3-year mean.