# Biobased plastic: A plausible solution to carbon neutrality in plastic industry

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# Biobased plastic: A plausible solution to carbon neutrality in plastic industry

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## Abstract

Biobased plastic combined with plastic recycling could be a plausible solution for achieving carbon neutrality by plastic industry. Herein we use production data, emission factors, and future plastic demands (2021–2060) to build a model, evaluating carbon neutrality under five scenarios. Our simulation indicates that carbon neutrality can be achieved by 2060 when biobased plastics takes 90% of plastic production with near 50% of recycling ratio. The amount of carbon captured through photosynthesis surpasses that of carbon released through plastic life cycle. Recycling reduces virgin plastic production, which is the primary carbon source. A one-fold increase in the use of recycled plastics could lead to a three-fold reduction of virgin plastic production. Existing plastics stored 6.82 giga tons of carbon (GtC) in 2020, serving as an

artificial carbon reservoir never recognized before. This carbon reservoir will expand to 23.0 and 27.4 GtC under 22% and 50% recycling scenarios, respectively, by 2060.

Achieving carbon neutrality is a key strategy for minimizing the aggregation of greenhouse gases (GHGs) in the atmosphere (*1-5*). Increasing carbon sequestration and reducing fossil fuel consumption are two primary solutions (*6, 7*). Photosynthesis of vegetation is a natural carbon sequestration mechanism, and vegetation sector currently stores 450–650 gigaton carbon (GtC) worldwide in the form of biomass (*8*). The capacity of biomass is limited by geographical and biological constraints, leading to highly variable sequestration permanence (*9-13*). Efforts have been made to create artificial carbon reservoirs for expanding carbon capacity and reducing its instability (*14*). One of these artificial reservoirs might be biobased plastic, which not only reduces fossil fuel consumptions, but also is a more stable and denser carbon form than biomass, resulting in better carbon sequestration (*15-18*).

Plastic production has been expanding rapidly since the 1950s. Conventional plastics made from fossil fuels constitute 99% of all produced plastics, consuming 8% of global petroleum and natural gas production (*19, 20*). Fossil carbon is not only the primary energy source for plastic synthesis, but also the elemental component of plastics. Thus, considerable amounts of fossil carbon are transformed to conventional plastics. The short service time of plastics generates huge amounts of waste which may become carbon sources again if not handled properly. To date, 76% of all produced plastics have been turned into solid waste (*21*). Improperly disposed plastics are generally resistant to decomposition, creating serious ecological issues (*22-25*). To battle plastic pollution, a variety of measures, such as use of degradable plastics, enhanced waste recycling, and incineration, are proposed (*26-30*). However, some of these measures have distinguished carbon footprints. As a result, complicated trade-offs are formed between plastic waste management and carbon emission control (*31-33*).

Biobased plastics are made from refined biomass feedstock, which originates from vegetation. The up-scaling of biobased plastics used to be subject to several constraints, including premium cost, sacrificing food supply, and technical obstacles for large-scale production. However, these disadvantages have been gradually offset by growing concerns on climate change, establishment of global carbon trading mechanisms, and development of new biobased plastics, and new synthetic technologies on traditional polymers *(34)*. The potential substitution ratio of conventional plastics is estimated at 90% *(35)*.

Despite these advances, the adaptation of biobased plastics is still in its early stage. The perspective of biobased plastics in realizing carbo neutrality for plastic industry remain to be quantified. The present study aimed to quantify the carbon neutrality potential of biobased plastics using a life cycle assessment model, estimating carbon capacity and net GHG emissions under different raw materials and post-use treatment scenarios. Since the next 40 years (2021–2060) are critical for realizing carbon neutrality (*36, 37*), the fate of plastics during this periods is simulated based on GHG emission factors (*21*) and recent production data (*38, 39*). Other parameters, such as post-use treatment ratio and usage lifetime under different plastic types and market sectors, are acquired from the literature and United States Environmental Protection Agency reports (*40*).

## Estimating future plastic production in different scenarios

Five scenarios are designed, i.e., no biobased plastic substitution with low recycling rate (22.4% of total plastic waste; scenario 1), 15% biobased plastic substitution rate with low recycling rate (scenario 2), no biobased plastic substitution with high recycling rate (49.7% of total plastic waste; scenario 3), 15% biobased plastic growth with high recycling rate (scenario 4), and 25%

biobased plastic growth with high recycling rate (scenario 5). The low and high recycling rates are determined based on previously reported results, as well as recent development of plastic recycling technologies (*19-21*). We intend to determine whether carbon neutrality for plastic industry can be achieved by biobased plastic substitution (Figs. S1–S5).

By 2020, the accumulated production of virgin plastics reached 9100 MT. Among all produced plastics, 3260 MT plastics remain in use, including 3000 MT virgin plastics and 260 MT recycled plastics (Fig. 1). The rest has turned into solid waste and entered the post-treatment phase. Post-use disposal options include but are not limited to recycling, incineration, and landfilling (*41, 42*). Plastic recycling began in the 1980s and 830 MT of plastics have been recycled until now (*43*). Incineration is accompanied with energy recovery in some cases, which has consumed 1300 MT virgin plastics and 100 MT recycled plastics (*44*). Landfilling is responsible for the majority of plastic waste on earth (*45, 46*). Since 1950, 5600 MT of plastic waste have been buried in landfills or released to the environment based on our simulation, which is consistent with a previous estimate (*21*).

## A growing carbon reservoir in plastics

Plastics in use and disposed but not destroyed have become one of the largest artificial carbon reservoirs. This reservoir had accumulated 6.82 GtC by 2020, equivalent to 25.0 gigaton $CO_2$ ($GtCO_2$). Although the plastic-carbon reservoir is much smaller than natural reservoirs in scale, it is easier to be accessed and manipulated by human activities and may become a potential carbon source if handled improperly. Meanwhile, 22.0 $GtCO_2$ of GHGs had been generated during virgin plastic production and post-use disposal.

The growing trend of virgin plastic production between 1950 and 2019 followed a cubic polynomial function ($R^2$ = 0.997; Fig. S6) and was rarely deterred by external events. Even the COVID-19 pandemic has posed little impact on plastic production, thanks to strong demand for medical consumables and personal protective gear (*47-49*). Aside from any major disruption in the world's political and economic systems, the growth of plastic production is expected to continue in the next few decades.

## Impacts of plastic recycling on carbon neutrality

A comparison between scenarios 1 and 2 (6900 MT; Figs. S1 and S2) and scenarios 3–5 (9300 MT; Figs. S3–S5) indicates that plastic recycling plays an important role in virgin plastic production, assuming the same quantity of plastics is retained in the use phase. To meet the global demand for plastics by 2060, the accumulated virgin plastic production in scenarios 1 and 2 is 46,000 MT, while 39,000 MT of virgin plastics is needed in scenarios 3–5. Each 2400 MT increment of recycled plastics can lower virgin plastic production by 7000 MT under the same magnitude of in-use plastics.

The impacts of plastic recycling are also reflected in carbon capacity and net GHG emission. Without substitution of biobased plastics, the capacity of the plastic-carbon reservoir is estimated to approach 27.4 and 23.0 GtC by 2060 under low and high recycling scenarios, respectively. Lower production of virgin plastics results in less accumulated plastic waste by landfilling (Figs. S2 and S4). At the same time, the net GHG emission approaches 127 and 112 $GtCO_2$, respectively. The main driver is virgin production, which explains the GHG emission gap between two recycling scenarios. The GHG emission by recycled plastic production or from per unit recycled plastic is less than 10% or 28% of that by virgin plastic production. Compared to landfilling and incineration, plastic recycling benefits both plastic pollution control and carbon neutrality. It should be noted that over 90% of recycled plastics can only be reutilized once, since the quality of recycled plastics decreases as the polymer chain becomes shorter than virgin plastics (*21*). From the GHG emission point of view, currently available recycling technologies simply extend the lifetime of plastics in the use phase, plastic waste eventually goes for incineration and landfilling.

## Reduced carbon footprints with bio-based plastics

Scenarios 2 and 4 resemble the circumstances under which biobased plastics continuously replace conventional plastics with low and high recycling rates corresponding to scenarios 1 and 3, respectively (Figs. S2 and S4). The main difference is to gradually increase the production of biobased plastics, which is estimated to increase at an annual growth of 15% from 4.56 MT in 2020 to 1284 MT (scenario 2) and 942MT (scenario 4), respectively, in 2060. It is worth noting that bio-plastic production also generates GHG emissions. A 8.03–28.1% reduction in GHG emissions during virgin plastic production can be achieved on given plastics types with the current manufacture technologies and combined energy sources (*50*).

Model simulation indicates that the net GHG emission in vegetation substitution scenarios drops to 99 $GtCO_2$ (Fig. S3; low recycling rate) and 84 $GtCO_2$ (Fig. S5; high recycling rate). Using biomass as raw material for plastic production adds an extra route to transform atmospheric $CO_2$ back to biomass. An extreme case (scenario 5) with an annual biomass substitution growth of 25% (Fig. S6) suggests that the amount of absorbed $CO_2$ in the atmosphere increases from 21 $GtCO_2$ to 45 $GtCO_2$, but the GHG emission during virgin production further declines from 79 $GtCO_2$ to 72 $GtCO_2$. As a result, the accumulated net GHG emission is 52 $GtCO_2$.

Although the amounts of carbon stored in the plastic-carbon reservoir remain the same under different substitution scenarios, the ratios of natural carbon and fossil carbon are different (Fig. 2). In scenarios 1 and 3, almost all carbon is derived from fossil fuel, with potential capacities of 27.4 and 23.0 GtC, respectively. As vegetation substitution grows, the ratio of natural carbon gradually surpasses that of fossil carbon. Thanks to the rapid substitution rate, scenario 5 has the highest natural carbon content by 2060, with 45 $GtCO_2$ originating from atmosphere (Fig. S5). The growing ratio of natural carbon is mainly contributed by the expansion of plastic production, rather than by replacement of the existing fossil carbon stock (Fig. S7). The ratio of biobased plastics in accumulated production (Fig. S7) is higher than that in reserved carbon (Fig. 2), indicating most biobased plastics are still in the use phase.

## Possible scenarios to approach carbon neutrality

The capacity of the plastic-carbon reservoir is growing with increment of production scale; however, the accumulated net GHG emission is growing even faster as more plastic waste is incinerated. This pattern can be observed in both scenarios 1 and 3, where almost no bioplastic is produced (Figs. 3a and 3c). By comparison, when biobased plastics are used to substitute conventional plastics, the net GHG emission is significantly reduced under the same carbon reservoir capacity (Figs. 3b, 3d, and 3e). As the proportion of biobased plastics increases, the accumulated net GHG emission decreases, as more emissions are absorbed by growing vegetation and transformed into biobased plastics.

The trends of annual net GHG emissions further exhibit the consequences of biomass substitution and plastic recycling (Fig. 4). The annual net GHG emissions in scenarios 1 and 3 are positively correlated with production scales. Higher recycling rates generate less GHG emissions in scenario 3 than in scenario 1 as a result of reduced production of virgin plastics. However, once these plastics exit the use phase and are incinerated, fossil carbon would eventually turn into $CO_2$ and release to the environment. It is therefore impossible to approach carbon neutrality.

The net GHG emissions in scenarios 2, 4, and 5 are quite distinguished from those in scenarios 1 and 3 (Fig. 4). With increasing biomass substitution, the annual net GHG emissions remain upward trends initially, peak between 2030–2050, and finally decline toward carbon neutrality. In 2060, the net GHG emission in scenario 2 is expected to reach 0.5 $GtCO_2$ $yr^{-1}$, approaching the net GHG level in 2000. The peak appears at 2047 with GHG emission at 2.4 $GtCO_2$ $yr^{-1}$. In scenario 4, the net GHG emission peaks at 1.8 $GtCO_2$ $yr^{-1}$ in 2045 and drops thereafter, approaching carbon neutrality by 2060. A comparison of scenarios 1-4 indicates that increased plastic recycling can reduce the peak of net GHG emissions under the same biomass substitution rate.

Rapid biomass substitution under scenario 5 fast forwards carbon neutrality to around 2043, with GHG emission peaking at 1.5 $GtCO_2$ $yr^{-1}$. After carbon neutrality is reached, the net GHG emission makes a sharp turn and reverses the downward trend to a steady state right below the carbon neutrality line. Beyond this point, the GHG emission and carbon sequestration reach dynamic equilibrium, and GHG contribution by plastic industry is mitigated (Fig. 4).

## Sensitive analysis on model parameters

To explore ways for enhancing carbon sequestration, we further examine how biobased plastic substitution rates, incineration emission factors, and emission factors with virgin production can push the dynamic equilibrium as far as possible from the neutrality line, so that carbon sink dominates carbon source. Figure 5 shows changes in the equilibrium values when a given parameter varies by ±10% from the carbon neutrality line. Obviously increased biobased plastic substitution leads to the largest shift toward carbon sink. The GHG emission factor is also critical for carbon neutrality. Because biobased plastics dominants the plastic production near carbon neutrality, the GHG emission factor of biobased plastics is much more important than that of conventional plastics (Fig. 5). Reducing GHG emissions from virgin production depends on the substitution of fossil fuel with renewable energy, while any decline of incineration emission factors is heavily relied on the control of other GHGs.

The results reported herein may be beneficial for policy makers in facilitating biomass-based plastic production, which could transform a carbon source to a controllable carbon sink. Moreover, plastic recycling could reduce the consumption of raw materials, lower GHG emissions during production processes. These results could also facilitate governmental decision-making processes on how best to meet carbon neutrality targets under the Paris Agreement. With significant substitution of fossil fuel by biomass for plastic production, the industry could reach carbon neutrality between 2050 and 2060.

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## Author contributions

E.Z. initiated the project. E.Z. and X.S. conceived and designed the study. X.S. and M.X. collected all the data. X.S., M.X., and E.Z. contributed to the model configuration and data analyses. X.S. and E.Z. co-wrote the manuscript. All authors contributed to the data interpretation and manuscript editing.

## Competing interests

Authors declare no competing interests.

## Additional Information

**Data and materials availability:** Our model data can be found in the Supplementary materials.

**Supplementary information** is available for this paper at:

**Correspondence and requests for materials** should be addressed to E.Y.Z.

**Reprints and permissions information** is available at www.nature.com/reprints.

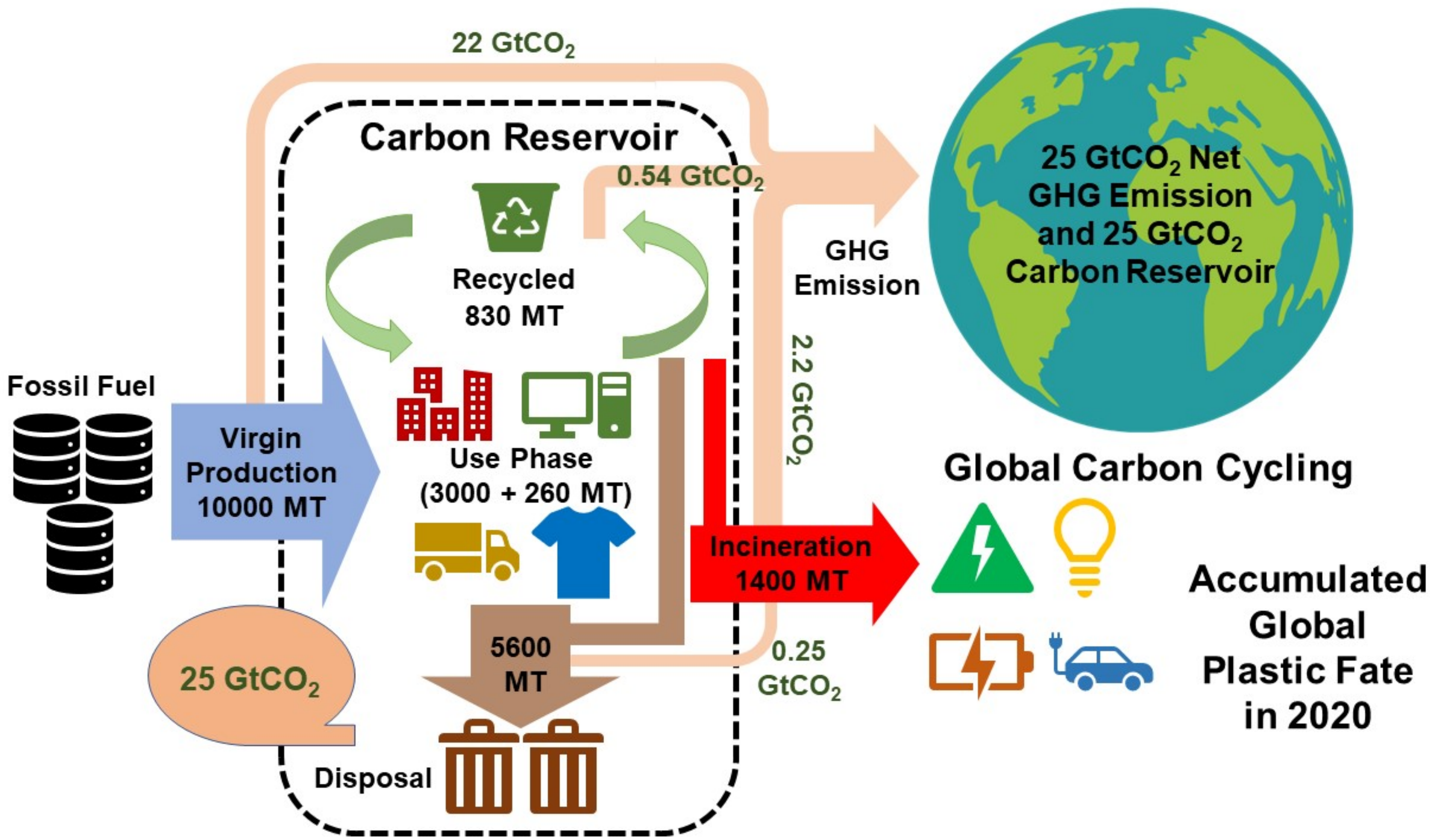



**Fig. 1. Plastic life cycle and net greenhouse gas (GHG) emissions in 2020.**

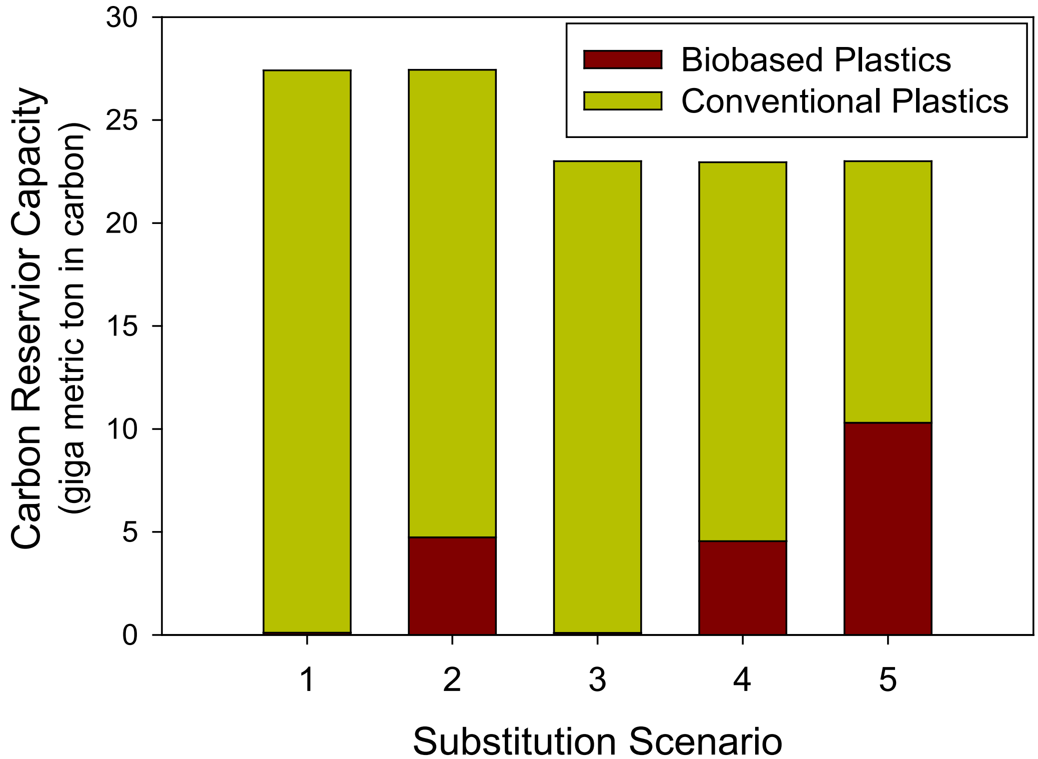



**Fig. 2. Capacity and components of the plastic-carbon reservoir under various substitution scenarios.**

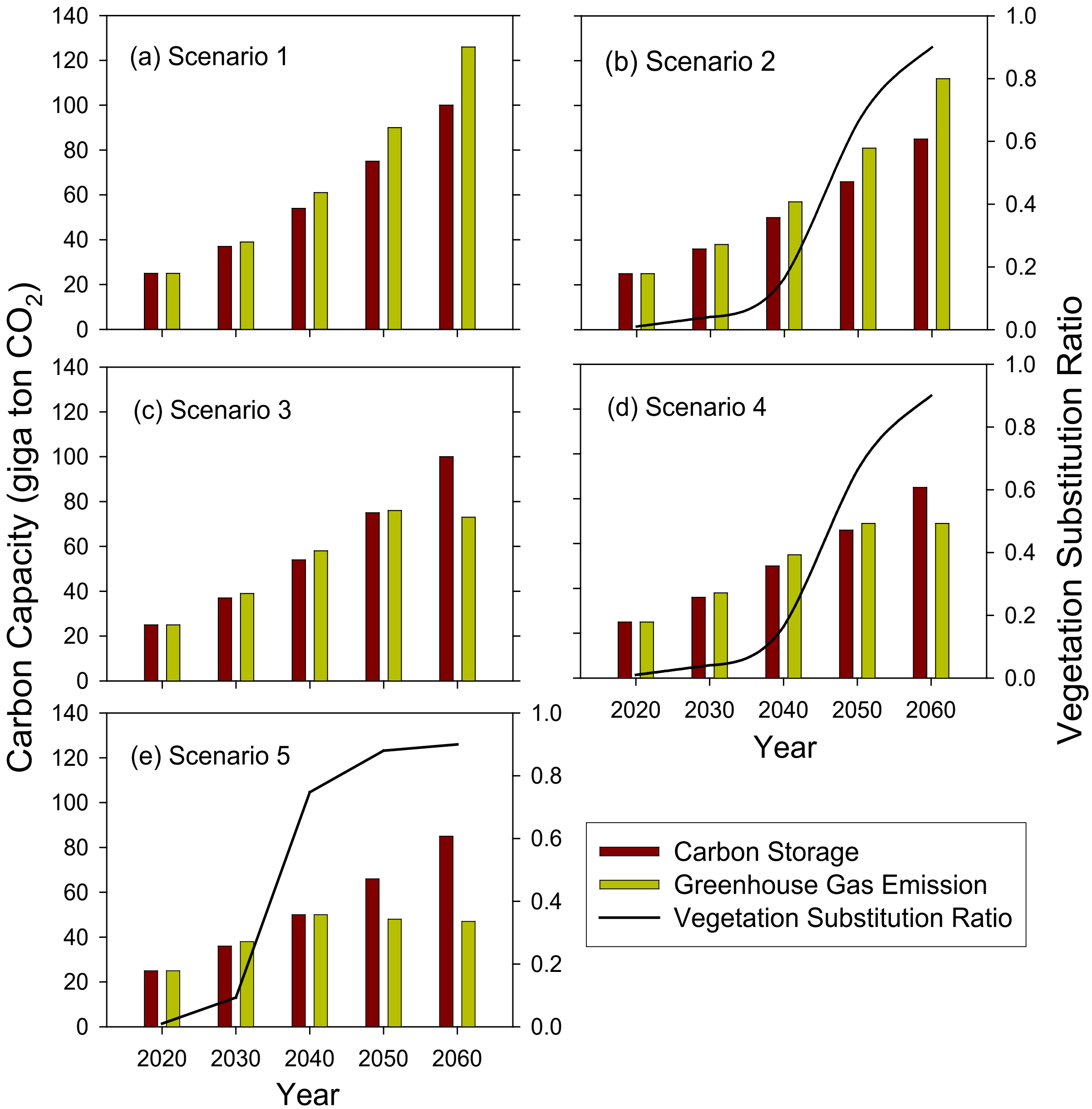



**Fig. 3. Accumulated net greenhouse gas (GHG) emissions and carbon storage capacities under different scenarios.**

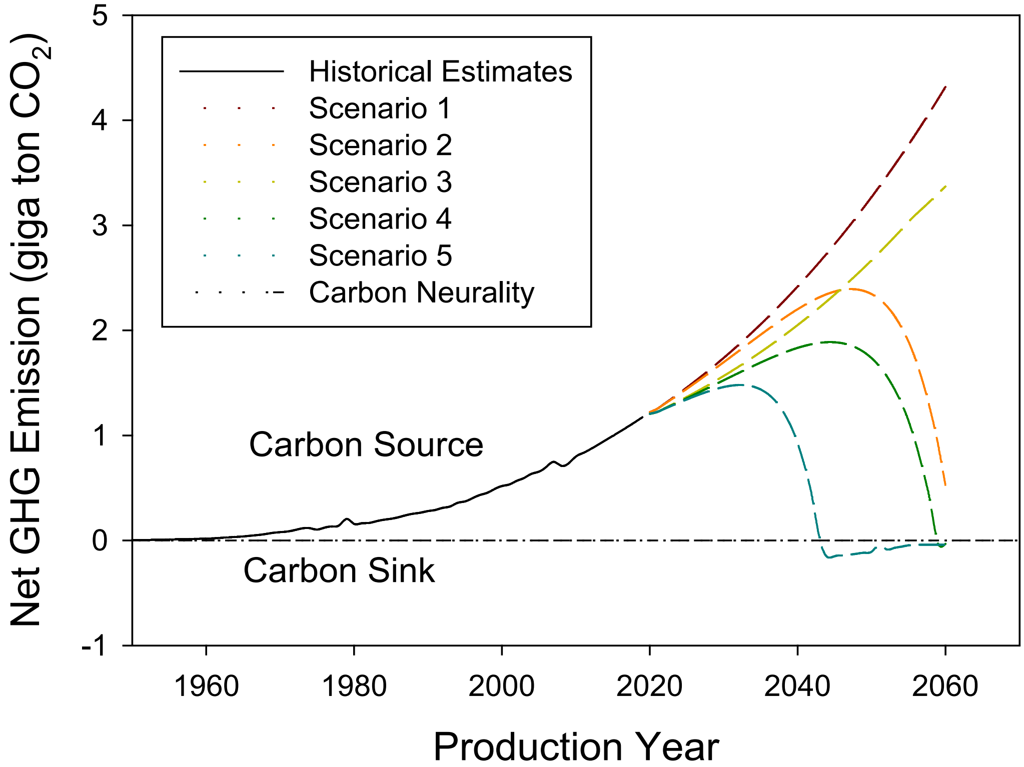



**Fig. 4. Annual net greenhouse gas (GHG) emissions under different biobased plastics substitution rates and recycle scenarios.**

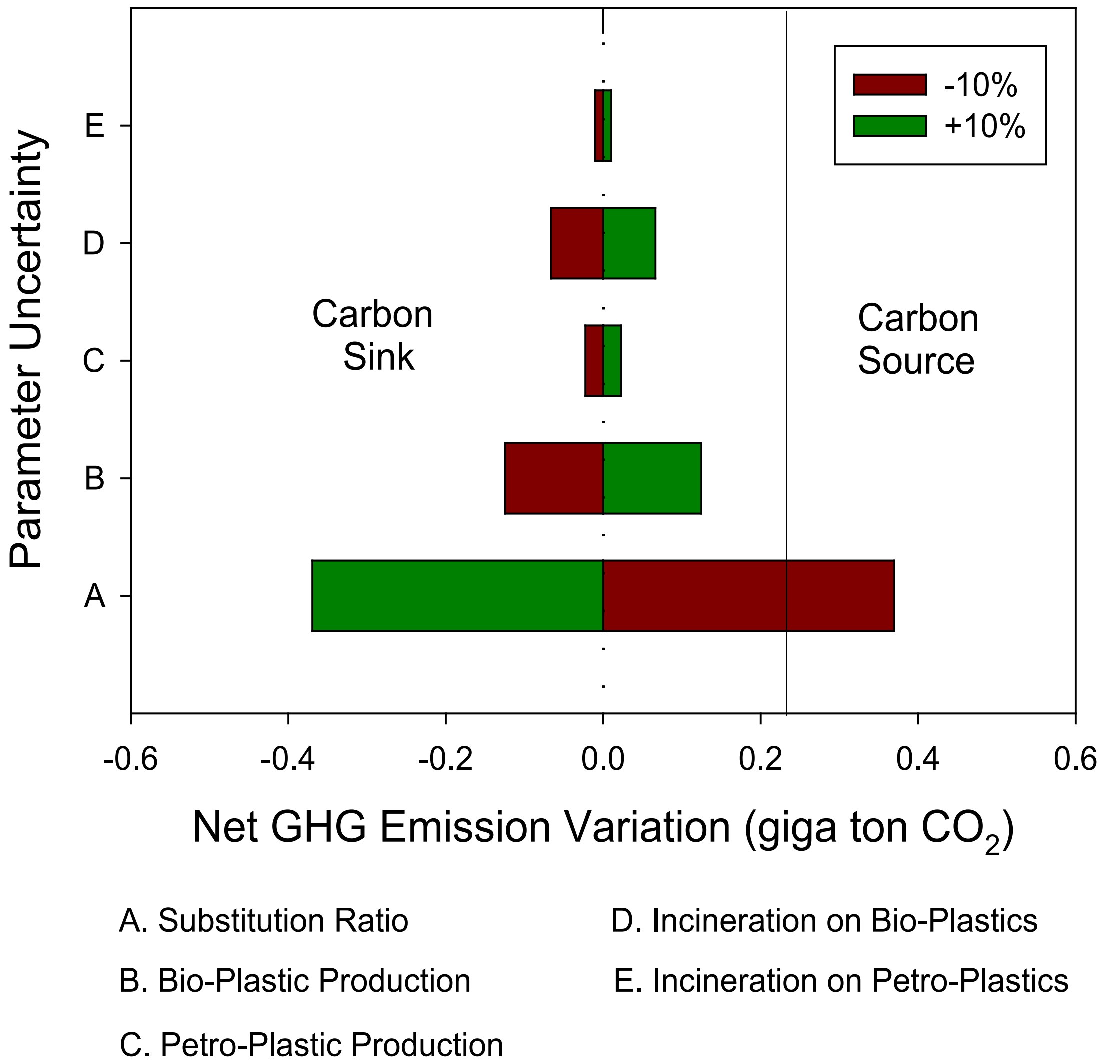



**Fig. 5. Sensitive analysis on key parameters for net greenhouse gas (GHG) emissions.**

## Methods

### 1. Model construction

A life cycle assessment (LCA) model is constructed to estimate carbon fluxes and greenhouse gas (GHG) emissions from global plastic production and post-use disposal. The carbon fluxes from seven plastic types and eight usage sectors are simulated and analyzed under different raw materials and post-use disposal strategies, including (but not limited to) recycling, incineration, and landfilling. The natural degradation of plastics is neglected due to their strong resistance against decomposition. On this basis, the impacts of plastic industry on global carbon cycling are comprehensively evaluated. The parameters during model design include raw material substitution, production scale, energy source, and waste disposal plan. The model does not consider the following factors: degradability, wear loss, manufacturing difference, emerging technology, newly synthetic plastic, and processing loss.

Seven types of plastics are assessed in this model, including high-density polyethylene (PE), low-density and linear low-density PE (LDPE & LLDPE), polypropylene (PP), polyvinyl chloride (PVC), polyurethanes (PURs), polyethylene terephthalate (PET), and polystyrene (PS), which account for over 95% of all produced plastics. Moreover, seven market sectors are defined as transportation, packaging, building and construction, electrical/electronic, consumer and institutional products, industrial machinery, and others. The mean and standard deviations of plastic lifetime in different market sectors are different, but they are assumed to follow log-normal distributions *(21)*.

Except for the usage phase sector, all other sectors generate extra GHG emissions during production, post-disposal, and transportation processes. The GHG emissions from the production and recycling sectors are combined with process energy, transportation energy, and process non-energy (*40*). For the incineration sector, the GHG emission is mainly derived from plastic combustion. The GHG emission from landfilling includes transportation energy only.

For biobased plastic production, an extra carbon flow is created to connect the atmosphere and biomass (vegetation) sectors, representing absorption of carbon dioxide by vegetation. During model simulation, only carbon contents which are transformed to plastics are calculated. Other consumption of biomass during production is thought to ultimately decompose back to carbon dioxide, which offsets the carbon dioxide absorbed from the atmosphere.

## 2. Key processes for model simulation

The key components of the LCA model includes virgin plastic production, waste generation/allocation, carbon capacity, and net GHG emission. Other details are listed in the supplemental materials, such as post-treatment sectors, carbon contents in plastics, and uncertainty evaluation methods (Text S1). The model is mainly programed through Python 3.7 with Pandas, Scipy, and Math packages.

### *2.1. Virgin plastic production*

The production of virgin plastics follows a cubic polynomial function assuming no other factor affects the production growth:

$$P_{low\ recyling}^{year} = 5 \times 10^{-5} year^3 - 0.207 year^2 + 202.46 year + 0.55 \qquad (1)$$

The regression fits well with $R^2 = 0.997$, and the cumulative error is less than 2.8% between 1950 and 2019.

However, different recycling ratios lead to different ratios of recycled plastics in the usage phase. To fulfill the same demand of plastics in the usage phase, the plastic production curve is bended to the right, with a production prediction as below:

$$P_{high\ recycling}^{year} = 4 \times 10^{-4} year^3 - 0.025 year^2 + 0.3 year + 160 \quad (2)$$

*2.2. Plastic waste generation*

The lifetime of plastics in the usage phase follows a log-normal distribution:

$$W_{i,j}^{k} = \sum_{t=0}^{k} P_{i,j}^{t} [CDF(t) - CDF(t-1)] \times \varepsilon_{i,j} \ \ (t \leq k, i = 1,2, \dots, 7, j = 1,2 \dots, 8) \quad (3)$$

where $W_{i,j}^{year}$ denotes the amount of plastic waste generated in the *k*th year for plastic type *i* with market sector *j*; $P_{i,j}^{t}$ is the plastic production in the *t*th year for plastic type *i* with market sector *j*; *CDF*(*t*) is the cumulative distribution function of a log-normal distribution with mean and standard deviations of lifetime in plastic type *i* with market sector *j* at year *t*; and $\varepsilon_{i,j}$ represents the proportion of plastic type *i* with market sector *j* in all plastic production.

*2.3. Capacity of plastic carbon reservoir*

The plastic carbon reservoir includes only carbons in the plastic form. At any given time, the capacity of the plastic carbon reservoir is calculated with plastics accumulated in the usage and landfilling phases:

$$M_{t}^{carbon} = \sum_{i=1}^{7} \delta_c * (U_i + W_i^D) \quad (4)$$

where $M_{t}^{carbon}$ is the carbon content; $\delta_c$ is the carbon content ratio in plastic *i*; $U_i$ is the plastic quantity in plastic *i* in the usage phase; and $W_i^D$ is the plastic quantity in plastic *i* in the landfilling sector.

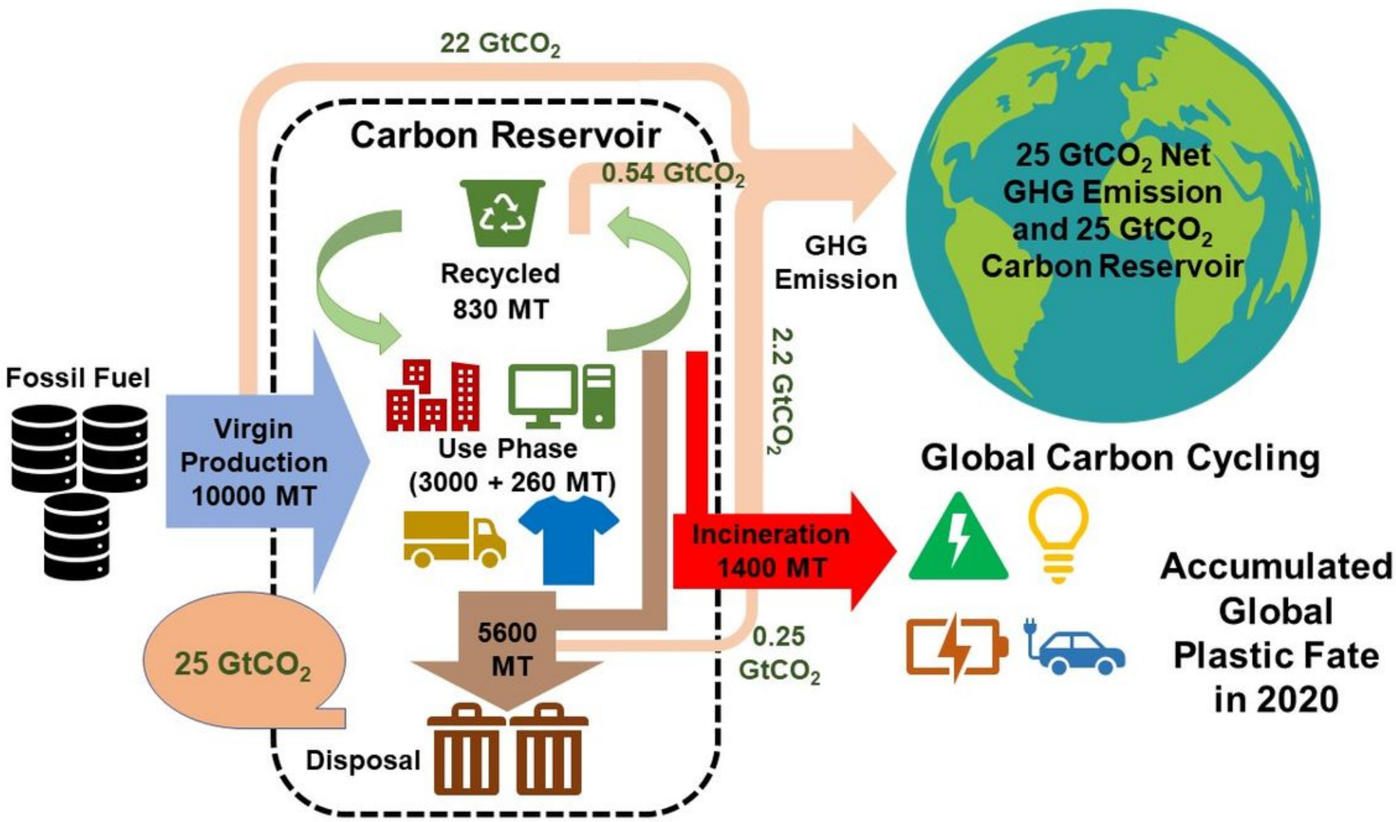
## 2.4. *Net greenhouse gas emission*

The GHG emission ($G$) is calculated by

$$G = F \times M \tag{5}$$

where $F$ is the emission factor of a given process and $M$ designates the amount of produced plastics which generates the emission.

# Figures




#### Figure 1

Plastic life cycle and net greenhouse gas (GHG) emissions in 2020.

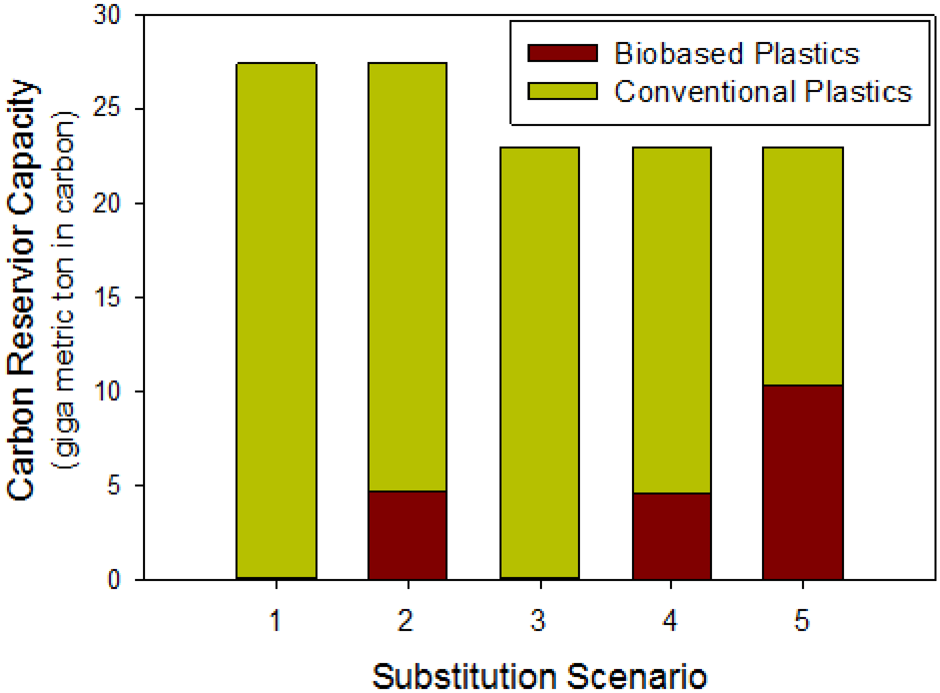



**Figure 2**

Capacity and components of the plastic-carbon reservoir under various substitution scenarios.

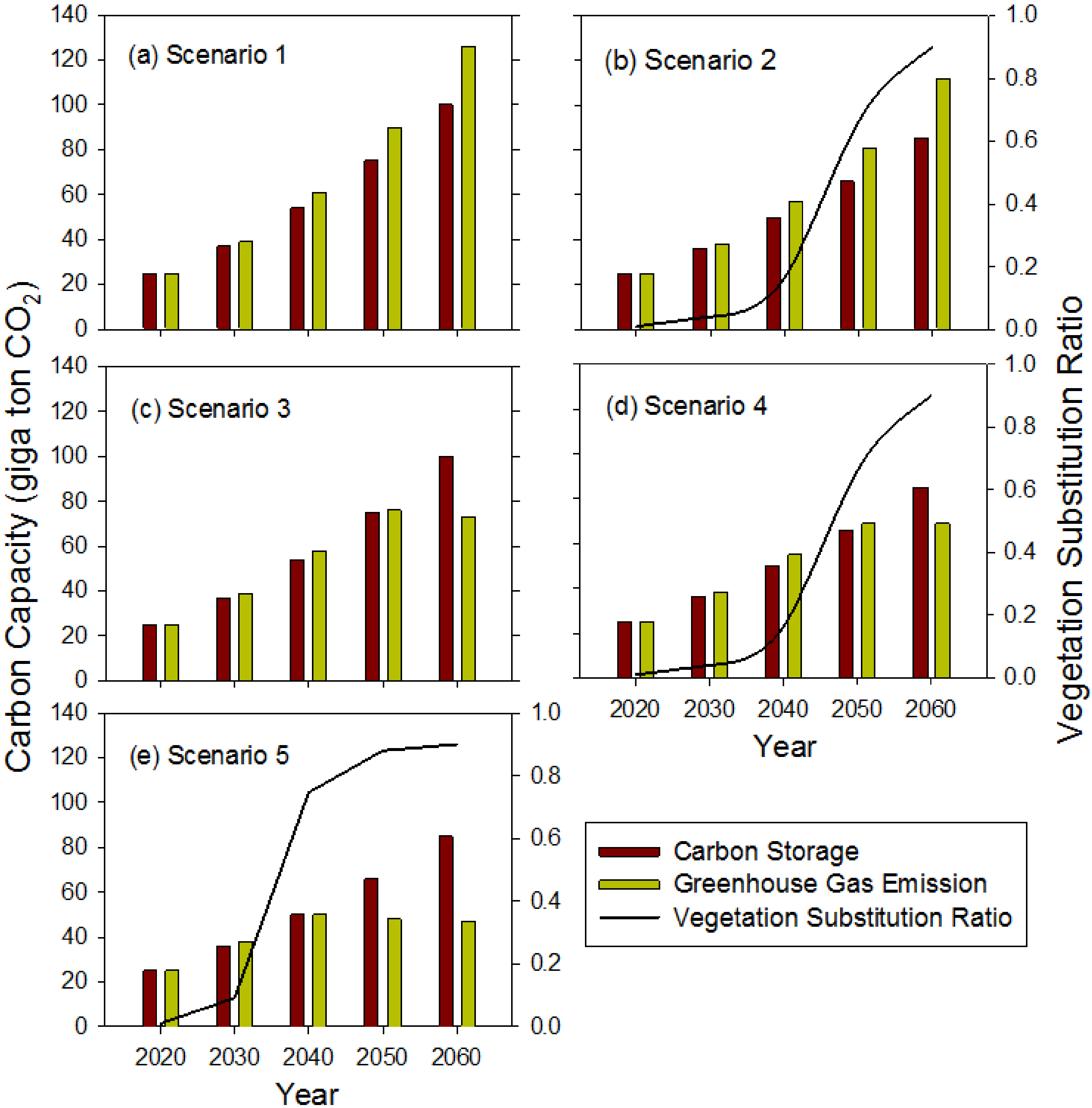



**Figure 3**

Accumulated net greenhouse gas (GHG) emissions and carbon storage capacities under different scenarios.

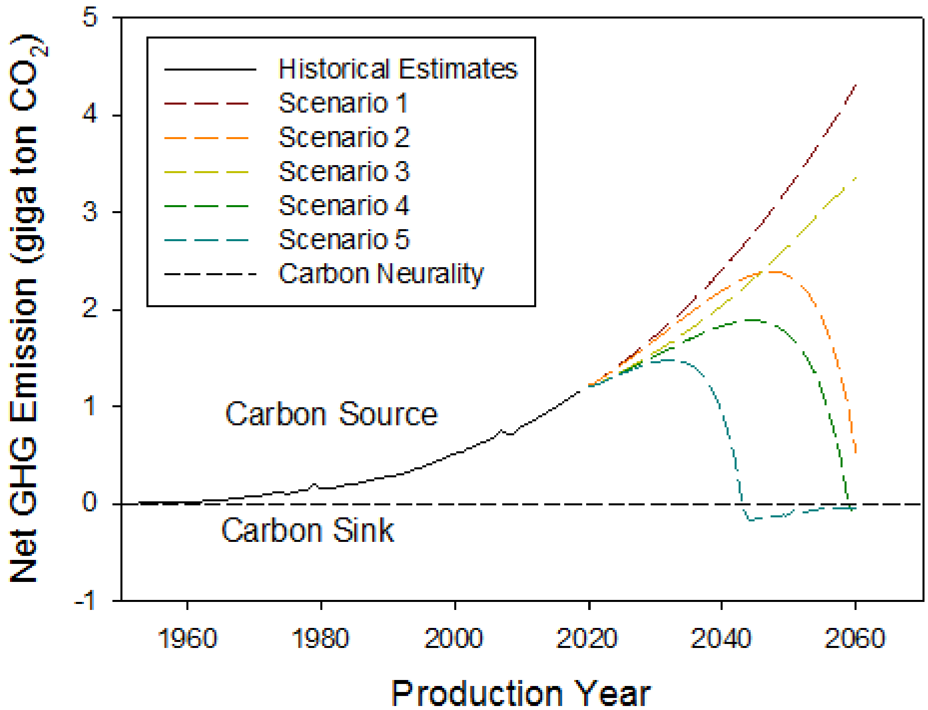



**Figure 4**

Annual net greenhouse gas (GHG) emissions under different biobased plastics substitution rates and recycle scenarios.

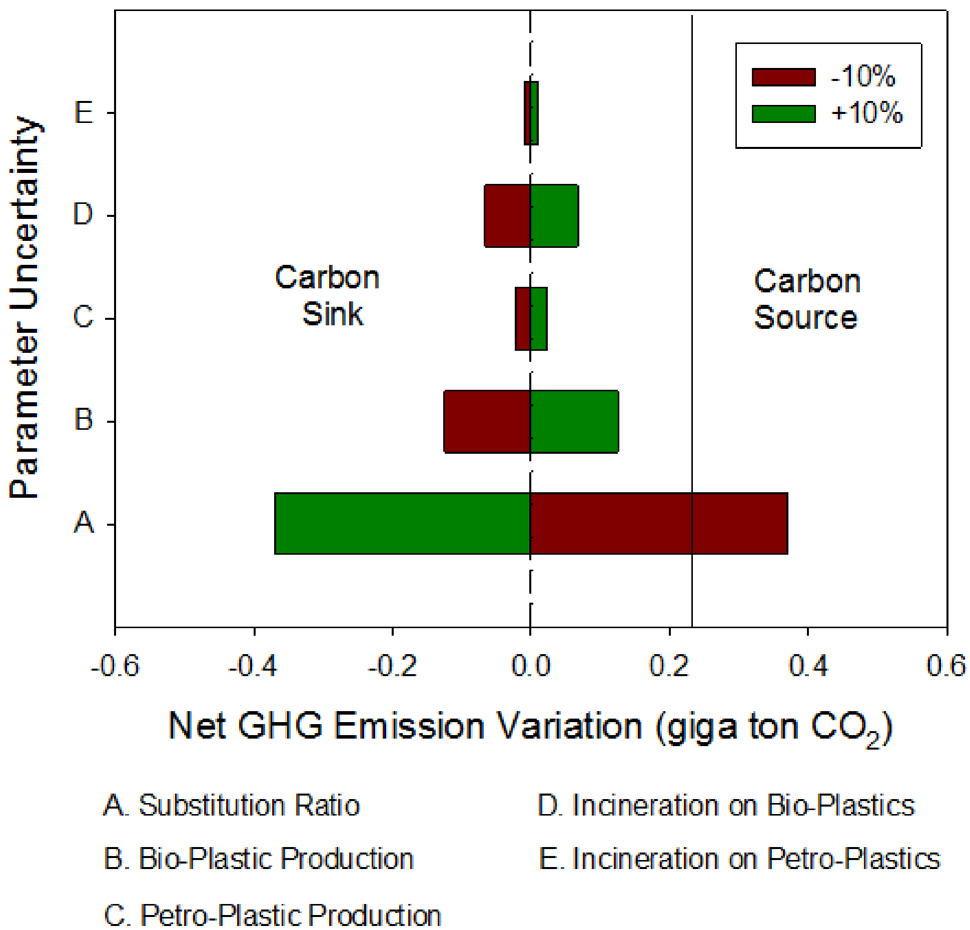



**Figure 5**

Sensitive analysis on key parameters for net greenhouse gas (GHG) emissions.

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- DataS2.GlobalPlasticProductionPrediciton.xlsx
- DataS3CalculationParametersforBiomass.xlsx
- SequestionoffossilcarbontoachievecarbonneuralizationSI1.docx
- DataS1.CalculationParameters.xlsx