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Carbon emissions due to deforestation for the production of charcoal used in Brazil's steel industry

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Steel produced using coal generates 7% of global anthropogenic CO_2 emissions annually[1]. Opportunities exist to substitute this coal with carbon-neutral charcoal sourced from plantation forests to mitigate project-scale emissions[2] and obtain certified emission reduction credits under the Kyoto Protocol's Clean Development Mechanism[3]. This mitigation strategy has been implemented in Brazil[4,5] and is one mechanism among many used globally to reduce anthropogenic CO_2 emissions[6]; however, its potential adverse impacts have been overlooked to date. Here, we report that total CO_2 emitted from Brazilian steel production doubled (91 to 182 $MtCO_2$) and specific emissions increased (3.3 to 5.2 $MtCO_2$ per Mt steel) between 2000 and 2007, even though the proportion of coal used declined. Infrastructure upgrades and a national plantation shortage increased industry reliance on charcoal sourced from native forests, which emits up to nine times more CO_2 per tonne of steel than coal. Preventing use of native forest charcoal could have avoided 79% of the CO_2 emitted from steel production between 2000 and 2007; however, doing so by increasing plantation charcoal supply is limited by socio-economic costs and risks further indirect deforestation pressures and emissions. Effective climate change mitigation in Brazil's steel industry must therefore minimize all direct and indirect carbon emissions generated from steel manufacture.

Growing global demand for steel, along with requirements to mitigate anthropogenic climate change, have increased the importance of reducing CO_2 emissions from steel production[7,8]. One mitigation strategy is to substitute the coal used as a reducing agent in steel production with biomass charcoal[9]. When this charcoal is produced from plantation forests grown on non-forested land (herein, plantation charcoal), it can be considered net carbon neutral under the UNFCCC Kyoto Protocol's Clean Development Mechanism (CDM) because carbon flux to the atmosphere during charcoal production and use is offset by carbon sequestration from plantation tree growth[10]. Substituting coal with plantation charcoal therefore mitigates CO_2 emissions from steel production at the project scale[2] and, when registered, can be used to offset emissions in Annex B countries, provided that plantation charcoal production is additional and does not generate indirect emissions from deforestation elsewhere[11,12].

More than half of Brazil's steel is produced using charcoal[13]. Historically, this charcoal was mainly sourced from native forests (herein, native charcoal)[13,14], generating carbon emissions to the atmosphere from wood harvest, carbonization and charcoal use[15,16]. However, the CDM provides policy and financial incentives in the form of Certified Emission Reduction (CER) credits to substitute the coal used in steel production with carbon-neutral plantation charcoal[3,10]. In 2000, the first CDM project of this type established tree plantations for charcoal production on cleared and degraded land[5]; later projects used this plantation charcoal in place of coal to produce steel and mitigate CO_2 emissions[4]. Despite approval of these projects as CER credits for utilization by Annex B countries, extensive charcoal production has also occurred outside the CDM framework to impact on Brazil's aggregate emissions as a non-Annex B country. The size of this impact is unknown.

In this study, we analysed annual steel production trajectories in Brazil between the years 2000 and 2007. We determined the quantity of each carbon source used in steel production (that is, coal, native charcoal and plantation charcoal; Supplementary Table 1) and quantified associated CO_2 emissions (Supplementary Table 3). We assumed all plantation charcoal qualified as carbon neutral under the CDM, whether or not it was produced by CDM-funded projects (<8% of plantation charcoal used in steel production[4]). In doing so, we assumed all plantations were planted on already cleared land (see Methods) and did not cause carbon leakage. We analysed results at the national and state level to investigate the spatial impacts of charcoal production and use in Brazil. Specifically, the state-level analysis focused on Minas Gerais, Brazil's most productive and industrialized steel and plantation charcoal producer[14,17] (Supplementary Fig. 1).

We found that annual steel production in Brazil increased between 2000 and 2007 (from 28 Mt to 35 Mt; Supplementary Table 1)[17] and relative coal use declined (from 50 to 46%; Fig. 1); yet annual CO_2 emissions from steel production doubled (from 91 ± 10 $MtCO_2$ to 182 ± 21 $MtCO_2$; Fig. 2 and Supplementary Table 3). Emissions increased owing to growing industry use of native charcoal outside of CDM-funded projects (Fig. 1 and Supplementary Table 1).

Native charcoal use in Brazilian steel production tripled (1.3 Mt–3.6 Mt) between 2000 and 2007 (ref. 13; Fig. 1 and Supplementary Table 1) in response to three main factors. First,

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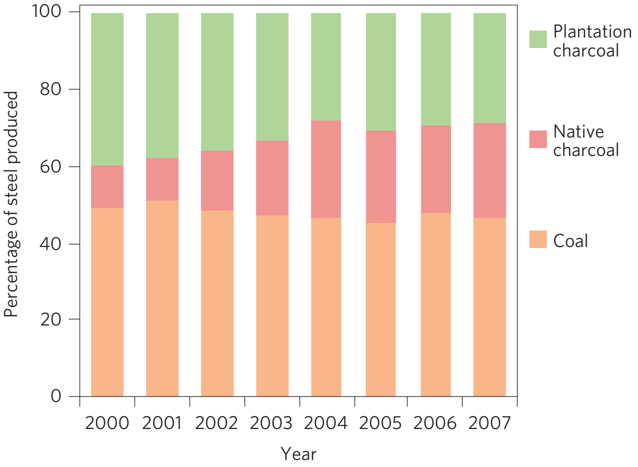

Figure 1 | Carbon sources used in Brazilian steel production between 2000 and 2007. Column series: Percentage of steel produced with coal, native charcoal and plantation charcoal.

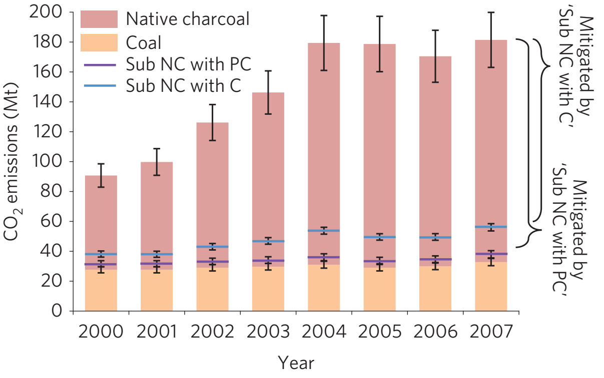

Figure 2 | CO_2 emissions from Brazilian steel production between 2000 and 2007. Columns show: emissions from steel produced with coal and native charcoal; emissions from steel produced with plantation charcoal were marginal (1 $MtCO_2 \pm 0.01$ in 2007; Supplementary Table 3). Lines indicate: emissions under hypothetical mitigation scenarios. 'Sub NC with C' being where native charcoal was eliminated by substitution with coal, and 'Sub NC with PC' being where native charcoal was eliminated by substitution with plantation charcoal. Differences between column and line series show mitigated emissions. Error bars illustrate 95% confidence intervals based on Monte Carlo uncertainty analysis (Supplementary Table 7).

steel production increased (Supplementary Table 1), driven by growing global and domestic demands[8]. Second, capability to use charcoal (in place of coal) in steel production increased as national industry infrastructure (specifically, blast furnaces) was refurbished in response to emerging CDM opportunities[4]. This new infrastructure did not permit a return to coal use (Supplementary Discussion 1). Third, a national-scale plantation charcoal deficit occurred, whereby increased charcoal demand surpassed national plantation supply[18]. This combination of factors increased the steel industry's reliance on charcoal for steel production at the national scale, and increased demand for native charcoal to meet the plantation shortfall in supply.

Unlike plantation charcoal, native charcoal is not considered carbon neutral under the CDM and carbon emissions from forest harvest must be reported under the UNFCCC in its harvest year. Throughout its life cycle, carbon is emitted to the atmosphere during deforestation for wood harvest, carbonization for charcoal production, and charcoal use in steel manufacture[15,16]. If these native forests were allowed to regrow, Brazil could take credit for carbon sequestration as it occurs; however, it is unclear if these forests regrow, at what rate, and how soon, if ever, they fully regain lost carbon. Therefore, in this study, our accounting captured all CO_2 emitted from native charcoal production and use, and assumed no native forest regrowth occurred following forest harvest.

We found that native charcoal use in steel production caused extensive deforestation and large net CO_2 emissions in Brazil. On average, 1 Mt of native charcoal caused 0.3 ± 0.04 Mha of deforestation and 1 Mt of steel produced with native charcoal caused 0.1 ± 0.01 Mha of deforestation (Supplementary Discussion 2). Clearing this extent of native forest emitted 19 ± 2 $MtCO_2$ per Mt of steel and total emissions of 940 ± 100 $MtCO_2$ between the years 2000 and 2007 (Supplementary Table 3). As a result, steel produced with native charcoal emitted up to nine times more CO_2 per tonne of steel than coal, and increased use of native charcoal relative to coal (Fig. 1 and Supplementary Table 1) increased average specific emissions from 3.3 ± 0.4 $MtCO_2$ per Mt steel in 2000 to 5.2 ± 0.6 $MtCO_2$ per Mt steel in 2007.

In this study, CO_2 emitted from native charcoal production was dependent on wood yield per hectare of forest cleared (Y_N). Decreasing Y_N would increase harvest area and thus increase associated CO_2 emissions, whereas increasing Y_N would have the opposite effect (Supplementary Discussion 3). In this study, we assumed Y_N ranged between 20 and 45 $m^3\ ha^{-1}$, which is a global average wood yield from charcoal-producing countries[16]. However, we also found evidence that Y_N could reach 100 $m^3\ ha^{-1}$ in Brazil[19] (Supplementary Discussion 3). If all native charcoal used in steel production was obtained from forests yielding this upper limit, CO_2 emissions from native charcoal would decline to one third those reported in Supplementary Table 3 (as described in Supplementary Discussion 3). Despite this, our main findings remain even under this unlikely scenario—increased native charcoal use increased CO_2 emissions from steel production between 2000 and 2007 and steel produced with native charcoal emitted (at least three times) more CO_2 per tonne of steel than coal.

The impacts of native charcoal production were not evenly distributed across Brazil. Seventy-two per cent (177 Mt) of Brazilian steel was produced in Minas Gerais[17], of which 18% used native charcoal for manufacture[13]. However, owing to stricter environmental law enforcement governing deforestation in Minas Gerais, 76% (9.7 Mt) of this native charcoal was imported from other Brazilian states (Supplementary Fig. 2). Specifically, most was produced in north and northeast Brazil (Fig. 3), where deforestation governance was relatively weak and charcoal production costs were low[18]. As a result, steel produced with native charcoal in Minas Gerais caused 3.3 ± 0.4 Mha of deforestation elsewhere in Brazil between 2000 and 2007 (Supplementary Discussion 2).

The spatial distribution of native charcoal use also influenced the ultimate quantity of deforestation and CO_2 emissions caused by steel production. On average, 33% (0.2 Mt) more native charcoal (and thus 6 ± 4 Mt of CO_2 emissions) was required to produce 1 Mt of steel outside Minas Gerais than inside this state (Supplementary Discussion 4). Relatively higher charcoal requirements were most probably due to less efficient carbonization technologies[16,20] and steel-making processes located far from industrial operations in Minas Gerais[18]. This spatial displacement of deforestation for charcoal production to states with relatively inefficient technologies further increased national-scale CO_2 emissions.

Projects substituting coal with plantation charcoal failed to reduce CO_2 emissions from steel production relative to coal at the national scale. This is because they did not prevent increased native charcoal use, which we found had a higher emission factor than coal. The 19% (47.8 Mt) of steel produced with native charcoal

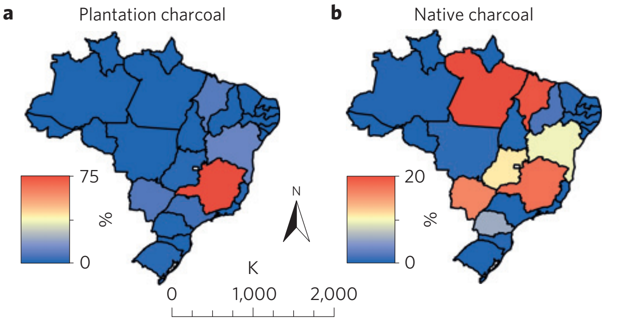

Figure 3 | Spatial distribution of charcoal production in Brazil between 2000 and 2007 (ref. 14). a, Plantation charcoal, of which most (75%) is produced in Minas Gerais. **b**, Native charcoal, of which most is produced in Pará and Maranhão. Ninety per cent of all charcoal produced between 1995 and 2008 was used for steel production[13]. Note the difference in scales between **a** and **b**.

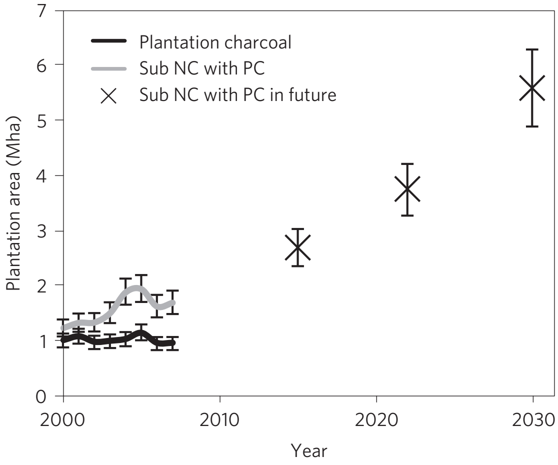

Figure 4 | Area required to produce plantation charcoal in Minas Gerais. Series: 'Plantation charcoal' is the land area (Mha) required to produce the plantation charcoal used in steel production between 2000 and 2007. 'Sub NC with PC' is the land area (Mha) required to also eliminate native charcoal use by substituting with plantation charcoal. 'Sub NC with PC' is the land area (Mha) required to also meet future steel demand between 2015 and 2030. Error bars illustrate 95% confidence intervals based on Monte Carlo uncertainty analysis.

caused 79% (930 ± 100 Mt) of all CO_2 emissions between 2000 and 2007 (Fig. 2 and Supplementary Table 3). Therefore, significant national emissions could have been avoided if native charcoal use had been eliminated. This has been recognized in some Brazilian states, where legal use of native charcoal is gradually being phased out (Supplementary Discussion 5). Substituting all native charcoal with coal could have avoided 71% (830 ± 10 Mt; Fig. 2) of CO_2 emitted from steel production between 2000 and 2007; however, these emissions would remain reportable as a carbon source under UNFCCC rules[10]. Alternatively, substituting all native charcoal with plantation charcoal could have avoided 79% (930 ± 20 Mt; Fig. 2) of CO_2 emitted. Although substituting native charcoal with plantation charcoal does not qualify for CER credits under CDM rules[10] (Supplementary Discussion 5), it would generate zero net emissions from charcoal use in steel production in Brazil's UNFCCC accounts. However, increasing plantation charcoal supply for this purpose is limited by the socio-economic costs of expanding plantations, and also risks further potential indirect impacts on native forests[21].

Increasing plantation charcoal production for CO_2 mitigation is land demanding. To produce enough plantation charcoal to both eliminate native charcoal use and meet steel demand, the area of charcoal plantations under rotation in Minas Gerais would have needed to increase from 0.9 ± 0.1 Mha in 2007 to 2.7 ± 0.3 Mha by 2015 (Fig. 4). Available land for plantation expansion in Minas Gerais is estimated between 5.9 Mha (ref. 18) and 12.4 Mha (ref. 22); however, given that annual plantation expansion was only 53,000 ± 1,000 ha between 2005 and 2011 (ref. 23; a period of rapid expansion) it is unlikely that plantation charcoal supply could have met 2015 demands even if expansion had occurred early enough for full charcoal production to be achieved (Supplementary Discussion 6). Insufficient annual expansion most probably reflects high socio-economic costs of plantation establishment and management[18] and a lack of financial incentives to do so.

Increasing plantation charcoal supply is also limited by multiple indirect impacts on native forests that could undermine their carbon mitigation potential[12]. For example, in Minas Gerais, we have previously shown that plantation expansion occurs preferentially over native forest regrowth to cause a decline in annual forest regrowth over time[21] (Supplementary Discussion 7). In this case, plantation expansion will not produce carbon-neutral charcoal unless compensatory reforestation occurs. In Minas Gerais, 30 ha of reforestation per 100 ha of plantations established in protected areas is legally required to mitigate this potential impact[24]. Therefore, increasing plantation charcoal supply in Minas Gerais to eliminate native charcoal use and meet future steel demand could require up to 0.5 ± 0.2 Mha of additional reforestation by 2015 (Supplementary Discussion 8). Although compensation effectiveness remains uncertain[25], the additional demand for land further increases the financial and social costs of producing sufficient plantation charcoal supply for steel production.

Increasing plantation charcoal production also risks other indirect sources of CO_2 emissions. For example, plantation expansion on pasturelands, if not guided by low-carbon rural planning, may compete with major crops and cattle ranching to cause land-use displacement, subsequent deforestation, and increased emissions[26,27]. Although CDM projects supposedly account for these potential indirect CO_2 emissions[10], the impacts of other non-CDM charcoal plantations are unknown. Furthermore, increasing plantation charcoal use for steel production may divert wood from other end uses, such as pulp and paper production[18]. This impact was not evident in our data; however, its potential to occur emphasizes that comprehensive carbon accounting is necessary to capture all CO_2 sources and sinks between the land surface and atmosphere. Investigating these potential forms of indirect emissions requires a national-scale spatially explicit model of carbon dynamics, capable of responding to changes in biomass supply and demand across all sectors.

In Brazil, substituting coal with plantation charcoal in steel production did not reduce the industry's national-scale CO_2 emissions because native charcoal use increased. Conversion of steel-making infrastructure to use charcoal has increased demand from native forests, leading to greater emissions than either coal or plantation charcoal sources of carbon. Eliminating native charcoal use with coal could have avoided significant CO_2 emissions (Fig. 2), but this solution is contrary to CDM principles. Alternatively, large-scale substitution of coal with plantation charcoal is CDM-compliant, but is also limited by socio-economic costs of expanding plantations and risks further indirect deforestation pressures and emissions. Therefore, CO_2 climate change mitigation strategies must minimize all direct and indirect carbon emissions generated from steel production—including those from coal, native charcoal and plantation charcoal—to ensure increased use of carbon-neutral alternatives does not unintentionally increase emissions elsewhere in the land-use system.

Other steel-producing countries face similar risks to those quantified here for Brazil. For example, China produced 47% (724 Mt) of world steel in 2012 (ref. 8), consuming ~7% (488.5 Mt) of world coal[28]. Like Brazil, China is a non-Annex B party under the UNFCCC (ref. 3), thus substituting coal with plantation charcoal in Chinese steel production also qualifies for CER credits under the CDM. No such projects are currently registered; however, future approval will increase emissions from steel production if charcoal production drives deforestation at broader spatial scales. Further, increased emissions may be more intensive in China, given that China produces 22 times more steel than Brazil[8], and also has extensive native forests reserves[29].

Methods

Steel and carbon sources. We compiled best available data on annual steel production and carbon sources (coal, native charcoal and plantation charcoal) used in steel production in Brazil and Minas Gerais between the years 2000 and 2007. Supplementary Table 1 contains the raw data analysed in this study and Supplementary Table 2 describes data sources, their collection methods and assumptions. The 2000–2007 time frame was chosen for data availability and relevance to the start of CDM projects and the climate change mitigation strategy of substituting coal with plantation charcoal in steel production. We also obtained steel production projections between 2015 and 2030 (Supplementary Table 2) to investigate future possible trajectories.

CO_2 emissions. We quantified annual CO_2 emissions from each carbon source used in steel production using equations (1)–(7). We assumed steel production followed the blast furnace–basic oxygen furnace (BF–BOF) route, which is common in Brazil[4,30]. We quantified emissions using the approved CDM assessment methodology[10], which assesses both process emissions (emissions from coal and charcoal use in steel production) and upstream emissions (domestic emissions from coal and charcoal production and transportation). We assumed no wood residues or chemical volatiles were recovered during charcoal use in steel production, given these practices are not common in Brazil[4]. All equation variables are described in Supplementary Table 5, and equation parameters are shown in Supplementary Tables 6 and 7. Some parameters were set stochastically, using a distribution of literature-based means and standard deviations (Supplementary Table 6). For each equation below, 10,000 realizations were performed to quantify the mean and 95th percentile confidence interval to bound uncertainty in our results.

We quantified CO_2 emissions from steel produced with coal with equation (1).

$$\mathrm{CO}_{2\mathrm{C}} = (\mathrm{C} \times \mathrm{EF}_{\mathrm{C}}) - \left(\mathrm{S}_{\mathrm{C}} \times \mathrm{C}_{\mathrm{S}} \times \frac{44}{12}\right) + (\mathrm{C} \times \mathrm{EF}_{\mathrm{R}} \times D \times T) \tag{1}$$

where CO_{2C} is the CO_2 emitted from steel produced with coal; C is the coal used in steel production; EF_C is the CO_2 emission factor of metallurgical coal; S_C is the steel produced with coal; C_S is the carbon factor of steel; 44/12 is the conversion factor of carbon to CO_2; EF_R is the CO_2 emission factor of transporting coal by rail in Brazil; D is the distance travelled by rail from port to steel production regions in Brazil; T is the number of trips required per tonne of coal. All coal used in steel production was imported into Brazil[17] and we assumed this was transported from major ports to steel production regions by rail[4] (see Supplementary Fig. 1).

We quantified CO_2 emissions from steel produced with native charcoal with equation (2).

$$\mathrm{CO}_{2\mathrm{NC}} = \left(\left[\frac{\mathrm{NC} \times W \times \mathrm{C}_{\mathrm{AGWB}}}{Y_{\mathrm{N}}}\right] - [\mathrm{S}_{\mathrm{NC}} \times \mathrm{C}_{\mathrm{S}}]\right) \times \frac{44}{12} \tag{2}$$

where CO_{2NC} is the CO_2 emitted from steel produced with native charcoal; NC is the native charcoal used in steel production; W is the dry wood required per tonne of charcoal; Y_N is the wood yield per hectare of native forest, assuming all wood was harvested from a savanna forest (Supplementary Discussion 3); C_{AGWB} is the carbon lost from live aboveground woody biomass when savanna is cleared for native charcoal production (Supplementary Table 4); S_{NC} is the steel produced with native charcoal. Dead and belowground carbon losses were not included in our analysis. CO_2 emissions from transporting charcoal were ignored, as transportation distance was unknown; however, these emissions were considered small relative to those emitted during charcoal production and use (Supplementary Discussion 9).

We quantified CO_2 emissions from steel produced with plantation charcoal with equation (3).

$$\mathrm{CO}_{2\mathrm{PC}} = \mathrm{PC} \times \mathrm{EF}_{\mathrm{PC}} \tag{3}$$

where CO_{2PC} is the CO_2 emitted from steel produced with plantation charcoal; PC is the plantation charcoal used in steel production, which is sourced from both CDM-funded and non-CDM-funded plantation charcoal production projects; EF_{PC} is the CO_2 emission factor of plantation charcoal production, considering emissions from diesel used for tree establishment, management and harvest. As required by the CDM, all plantations were established on land cleared for at least ten years[10]; therefore, net carbon flux from aboveground woody biomass between plantation establishment and harvest was zero. We also assumed all non-CDM-funded projects established plantations on already cleared land. This was reasonable, given prior evidence that forests are not deforested for plantation establishment in Brazilian steel production regions[21].

Additional coal/plantation charcoal. We quantified the coal and plantation charcoal required to eliminate native charcoal used in steel production, using equations (4) and (5) respectively. We also quantified the areas required to produce the plantation charcoal used in steel production, and the additional plantation charcoal required to eliminate native charcoal used in steel production, with equations (6) and (7) respectively.

$$\mathrm{C}_{\mathrm{NC}=0} = \frac{\mathrm{C}}{\mathrm{S}_{\mathrm{C}}}(\mathrm{S}_{\mathrm{NC}} + \mathrm{S}_{\mathrm{C}}) \tag{4}$$

$$\mathrm{PC}_{\mathrm{NC}=0} = \frac{\mathrm{PC}}{\mathrm{S}_{\mathrm{PC}}}(\mathrm{S}_{\mathrm{NC}} + \mathrm{S}_{\mathrm{PC}}) \tag{5}$$

$$A = \mathrm{PC} \times W \times Y_{\mathrm{P}} \tag{6}$$

$$A_{\mathrm{NC}=0} = \frac{A}{\mathrm{S}_{\mathrm{PC}}}(\mathrm{S}_{\mathrm{NC}} + \mathrm{S}_{\mathrm{PC}}) \tag{7}$$

where $C_{NC=0}$ is the coal required to eliminate native charcoal used in steel production; S_{PC} is the steel produced with plantation charcoal; $PC_{NC=0}$ is the plantation charcoal required to eliminate native charcoal used in steel production; A is the area required to produce plantation charcoal used in steel production; Y_P is the annual plantation wood yield; $A_{NC=0}$ is the plantation area required to eliminate native charcoal used in steel production.

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Author contributions

L.J.S. designed the project and conducted the analysis. All authors analysed results and co-wrote the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to L.J.S.

Competing financial interests

The authors declare no competing financial interests.