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Potential of biochar with crop residues in maize systems of Kenya

Ex-ante assessment for strategic guidance of research, investment and policy

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Support program

ProSoil – The Global Programme “Soil Protection and Rehabilitation for Food Security” – is implemented by GIZ and intended to help smallholder farmers to learn about climate-smart, agroecological methods to protect their land from soil erosion and restore and maintain soil fertility. To that end, ProSoil is cooperating with governmental institutions and entities from the realms of science, research, the private sector and civil society to establish framework conditions that will promote change in agricultural and food systems.

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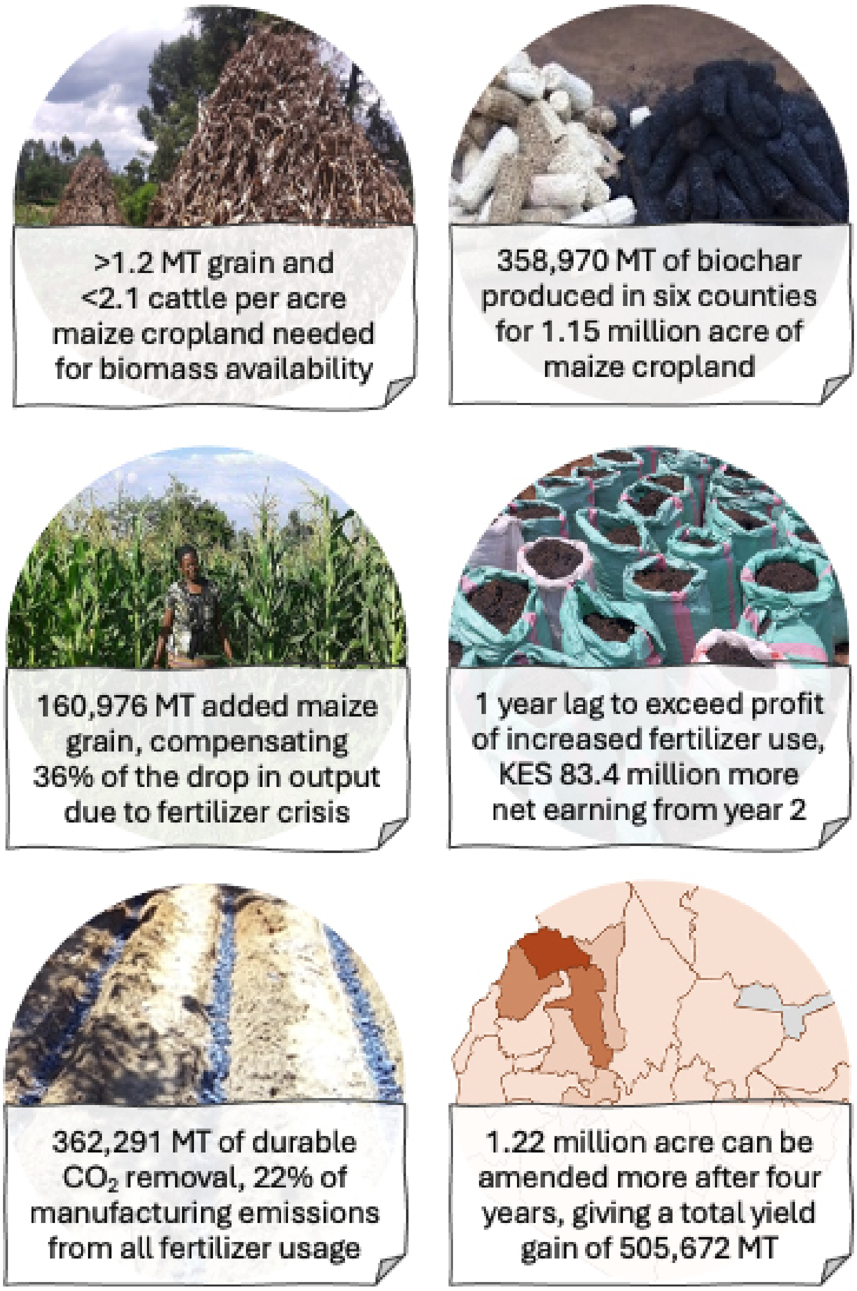
Highlights

Useable quantities of crop residue for biochar are dependent on productivity level and livestock density. In six counties excess residue is available for the practice and can close a large part of the production gap that arose from the surge in fertilizer prices. Investments in biochar are higher than for synthetic fertilizers over one season, but the financial benefits become greater thereafter. Sequestration of CO_2 and displacement of fertilizer would reduce the footprint of maize farming on the climate. Transfers between counties can uplift production at scale in the medium term.



Why this analysis

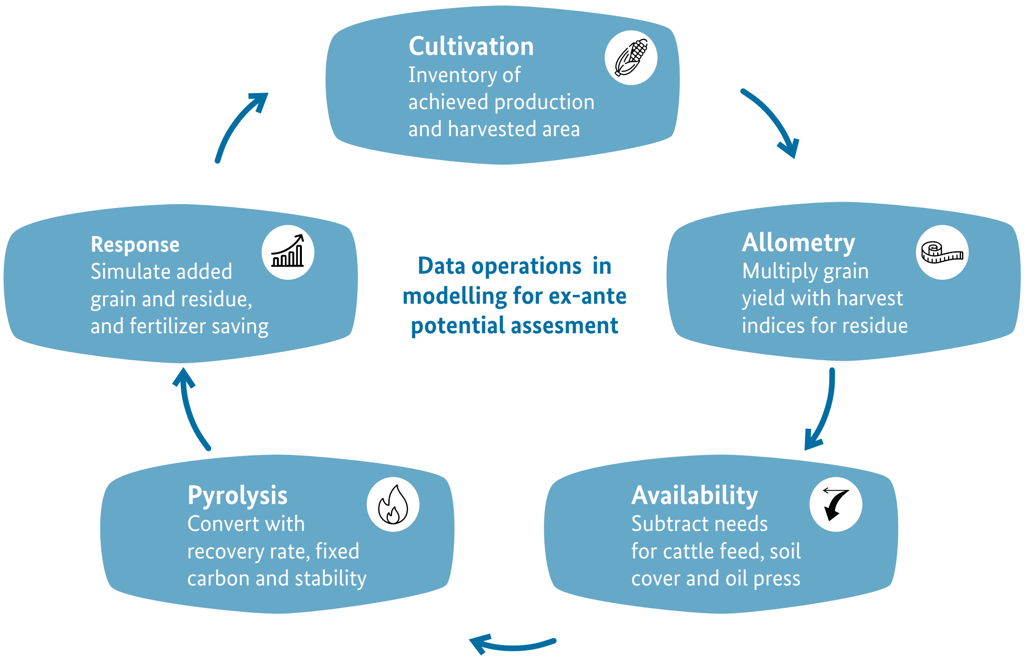
Kenya's cornerstone of food security and rural economy, that is maize cropping, faces severe threat from combined fertilizer price surges, and more frequent and intense drought. A 20-30% drop in production of maize grain[1] and doubling of retail price for flour over the past couple years causes shortage, poverty and malnutrition. To cushion the crisis, the Kenyan government is intervening through subsidies for 350,000 metric tons (MT) inorganic fertilizer and food aid distribution, costing the national budget upward from KES 4 billion (US $ 30 million[2]). Such intervention is not tenable over the long run and so there is urgent need for domestically produced solutions that address the root causes of low yield and fertilizer efficiency and can be deployed at scale. A difficult balancing act, since at the same time the environment and broader agricultural development must be safeguarded, and the overall input expenditure of farmers cannot be increased.

Turning excess agricultural residues into biochar via a process called pyrolysis has found traction in recent years due to its benefits for agricultural productivity through increased soil health, drought resilience, fertilizer efficiency and saving, and carbon removal. Evidence from field research and early scaling initiatives in Kenya not only confirms the tangible yield benefits of biochar but also that farmers observe these relatively quickly which is a significant factor in adoption. This presents an opportunity to use biochar as a solution for enhancing agricultural productivity and sustainability. Marketing of biochar-enriched synthetic fertilizers and organic inputs by multiple enterprises reflects a growing trend towards integrating biochar into mainstream agricultural practices.

Decisions on investment and policy require answers to key questions about the scalability, economic viability, and long-term effects of biochar use under realistic scenarios. Information on market size is key to drive advancements in delivery models, product formulation, regulatory frameworks, and fiscal incentives for effective and sustainable integration into the agri-food value chains. This ex-ante upscaled assessment aims to provide clarity on the potential scale and impact of biochar use in maize systems of Kenya by leveraging official data on land use, crop yields and fertilizer statistics, findings from research and case studies, all while accounting for varied need of residues, uncertainties and safety margins. A modelling procedure (Figure 1) with sequential operations starting from grain production data over standard conversion to residue quantities, deductions of competing pulls for livestock, resource recovery from pyrolytic processes, and dose-response yield gain was implemented that provides a comprehensive approach to evaluating agricultural efficiency and sustainability. As the benefit of soil health interventions is manifested over multiple years, these steps were looped, and legacy effects carried forth. Input data and conversion factors were furnished or reviewed by selected informants that are experts or practitioners in the field, ensuring robust and representative outcome. This framework and methods can be replicated across other geographic scales and regions. Besides the biophysical potential, the financial viability of biochar use was evaluated against prices of production, grain and fertilizer. The main factors used for conversion and response calculation are summarized in Annex #1. Results presented in this brief can help stakeholders anticipate the likely -outcomes and make informed decisions about the adoption and implementation.

1 WFP and BCG report (2022). Available here
2 Exchange rate USD to KES = 130

Figure 1. Data operation loop in modeling of potential for biochar use and impact.



What the numbers say

Resource availability

Input data for maize production and harvested area was retrieved from the county-level report for 2023,[3] stating a total grain output of 35.2 million bags or 3.18 million MT, and cultivation of 3.88 million acres in Kenya. Information was missing for Isiolo and Nairobi County, and inaccurate for Garissa and Mandera, which were excluded from the analysis. Production records are taken at trading centers and do not include what is directly consumed by households, hence actual figures would be higher. The quantity of residue was calculated using harvest indexes for separate parts, i.e., 2.2 for stover (straw) and 0.57 for shank (cob), as derived from observations in smallholder farming systems.[4] In total 8.82 million MT residue is produced in maize cropping across the country, with the top six counties accounting for 51%. Recalculated for the cultivated area, residue yields were lowest in Makueni County at 0.43 MT per acre and highest in Trans Nzoia County at 4.72 MT per acre.

3 Ministry of Agriculture and Livestock Development (2023). Available here

4 Roobroeck et al. (2019). Available here

Available stocks of residue were calculated by deducting usages for existing or recommended practices through nearest estimates. Losses during biomass aggregation were omitted as a non-removeable fraction of 5%. Offtake of shanks by oil pressing companies occurs but could not be accurately quantified and therefore a flat figure of 50% was factored in. County-specific adjustments for resource allocation to livestock were made on the basis of cattle numbers in the 2019 Agricultural Census.[5] Feed requirements were computed at 2 MT annual per head of dairy or beef, and 0.5 MT per head of boran free rangers, and at a formulation of three parts stover and one part shank, following advice from informant #2 and #5. Where shank was insufficient to meet livestock needs the difference was subtracted from stover quantities. Factors that can reduce biochar potential include higher residue use for roughage or silage (total 8-10 MT a year per dairy or beef cow), and stover sales occurring between farms. The provision of stover as mulch for covering soil surfaces was set at 0.61 MT stover per acre for all cultivated land, whereas the recommended rate is 1.22 MT per acre. Informants asserted that assumptions are realistic since use of maize residue for animals is limited by space and fresh fodder or hay are preferred because of higher nutritional value. Ubiquitous field burning of stover and piling up of shank at mills further confirm excess maize residue. On the basis of this "most likely" scenario, the thresholds for having availability of excess residue are a minimum of 1.2 MT grain per acre and a maximum of 2.1 heads of cattle per acre. In six counties these conditions are met and biomass resources from maize crop remain for biochar, which amounts to 1.44 million MT dry matter or 16% of the total biomass waste stock. This useable pool was converted to quantities of biochar at a 25% recovery rate which is the average for artisanal kilns stated by informant #3 and #4 and aligns with publications. In the first year, the total potential for biochar measures 358,970 MT, which ranged from 157,310 MT in Trans Nzoia to 1,245 in Nandi (Table 1). With full recirculation of biochar to the cropland area where residue was derived this volume translates to application rates between 0.62 and 0.01 MT per acre.

Table 1. Quantity and impact of biochar in the first year for counties with excess residue after deducting other needs.

Country	MT biochar produced (MT/acre application rate)	MT grain increase (% of yield drop in 2021-2022)
Trans Nzoia	157,310 (0.62)	70,789 (131%)
Uasin Gishu	95,007 (0.37)	42,753 (86%)
Bungoma	75,224 (0.34)	33,851 (80%)
Kakamega	15,860 (0.08)	7,137 (27%)
Elgeyo Marakwet	14,324 (0.19)	6,446 (65%)
Nandi	1,245 (0.01)	560 (2%)
TOTAL	358,970 (0.27)	161,537 (36%)

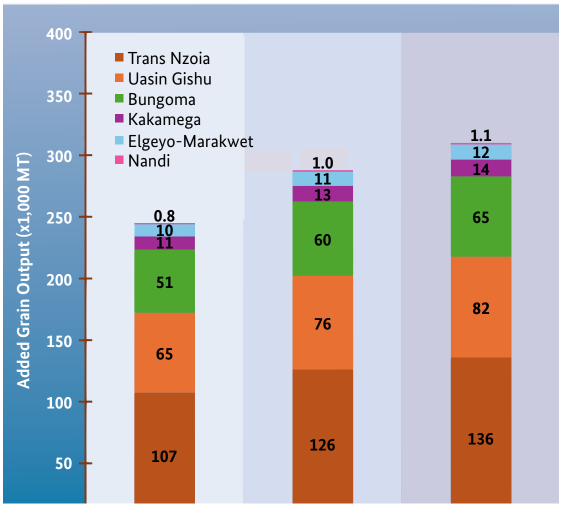
5 Ministry of Agriculture and Livestock Development (2019). Available here

Agricultural benefits

Calculations for grain yield response were based on a coefficient of 0.18 MT per acre for each 0.40 MT biochar per acre, derived from an IITA study with 150 farmer-managed trials which found mean gains of 0.11 to 0.29 MT under current fertilizer and manure input practices. The practical implementation used for this modeling exercise was the same, i.e., biochar placed inside the planting furrow and accompanying inputs remaining unchanged. Computing field-level response based on this set of conditions, shows that the counties of Trans Nzoia, Uasin Gishu, Bungoma, Kakamega and Elgeyo-Marakwet would see grain yield increments of respectively 3.1, 1.9, 1.7, 0.4 and 0.9 bags (90 kg) per acre in the first cycle of application. This is between 3.4 and 16% greater than before, and lifts production levels up to 13-22 bags per acre. In Nandi the yield increase would be 0.3% owing to the low amount of biochar produced and hence transfers of biochar within or between farms are needed for realizing tangible benefits. A total extra maize grain output of 161,537 MT or 1.79 million bags would be achieved across the six counties with effective potential, compensating for 36% of the drop in output at national level, and 2% to 131% of production loss at county specific level (Table 1).

Repeated application of biochar over consecutive seasons would lead to incrementally higher production since its effects on soil fertility are long-lived, as shown by a long-term experiment[6] as well as multi-locational trials6 of IITA. To account for this, the model was looped with a quarter of the biochar effect being carried over from the preceding season as adjustment for redistribution across the field by ploughing (Figure 2).

Figure 2. Production gain from repeated application of residue-derived biochar



Aside from that, the cultivated area, livestock numbers and allocation to fodder and mulch were kept constant, whereas the effect of yield increase on resource availability was taken along. In the second year of adoption, a total of 454,312 MT biochar could be produced in the six counties which is 26% above the first year, resulting to a total production gain of 244,824 MT or 2.72 million bags which is 52% above the first year. At this point the yield gain from applying residue-derived biochar would compensate 54% of the drop in output due to the fertilizer crisis. When looping the model over four years, the total biochar produced in the six counties would rise to 528,815 MT which is 32% greater than the first year, and a total production gain of 309,909 MT or 3.44 million bags would be generated which is 93% greater than in the first year.

6 Kätterer et al. (2019). Available here

Financial viability

Another key determinant of the potential for biochar is how the cost of the practice weighs up against the value from yield gains. In view of the preconditions for scaling, a third-party service delivery is emulated that allows to convert vast quantities of residue while maximally discounting costs through incomes from carbon credit. Companies, such as those from informant #3 and #4, are pursuing this strategy and quoted realistic selling price for biochar at KES 600 (US $ 4.5) per 50kg, wherein KES 1,300 (US $ 10) per 50kg is earned at the current rate of voluntary emission offset markets. On the side of revenue, the value of increased grain output was calculated at KES 4,000 (US $ 30.8) per 90 kg bag, reflecting the purchase price by the National Cereals and Produce Board (NCPB) in the previous last period[7]. The net profit of using biochar was compared to that of using fertilizer to achieve the same yield gain, providing insight on the opportunity cost for the practice. The required quantities for required fertilizer were calculated based on a mean agronomic efficiency of 25 kg grain per kg N observed under different conditions , equivalent to a 40 kg N input per acre for 1 MT grain per acre. The price of synthetic fertilizer was set at KES 6,500 per 50 kg bag as per the current rates in the open market. Ongoing subsidies program from the government, which cover almost half the purchase cost, were omitted for this assessment to make an even-handed comparison of biochar and fertilizer and discern macro-level feasibility and benefits.

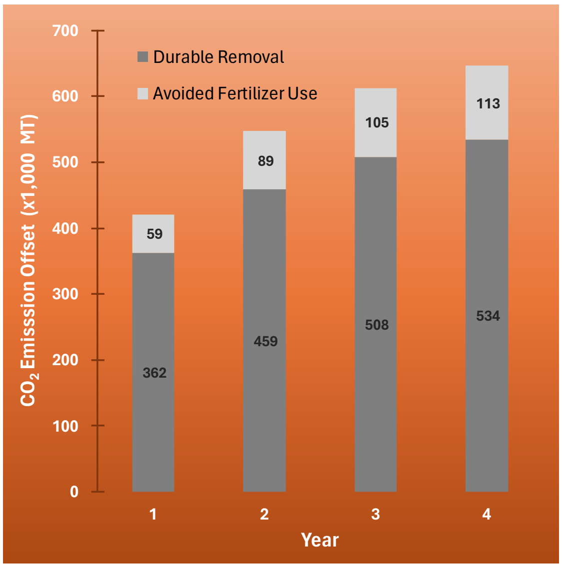
Figure 3. Econometrics of residue-derived biochar at field level over multiple application cycles; in Kenyan Shilling (KES) per acre.

7 NCPB statement (2023). Available here

Expenses per acre for farmers to acquire biochar from a service provider would range between KES 7,424 in Trans Nzoia and KES 96 in Nandi for in the first year of implementation (Figure 3). Net profit margins of KES 4,950 to KES 64 per acre would be achieved across the six counties, which is a function of the biochar input rate. Under the modelled conditions, the value cost ratio of the practice measures 1.67, whereas the general threshold for economic feasibility is two. Low levels of additional earning per acre in Nandi County underscore the need of resource transfers within or between farms so meaningful financial gains are achieved. Total extra net earnings in the six counties would be KES 2.87 billion (US $ 22.1 million) for the first year of implementation. When compared with the expenditure of increasing synthetic fertilizer to achieve the same yield gain it is found that use of biochar is less financially attractive for the first year, with negative opportunity costs of KES 1,130 to KES 15 per acre. In total, a profit of KES 656 million (US $ 5.05 million) would be foregone as opposed to the use of synthetic fertilizer.

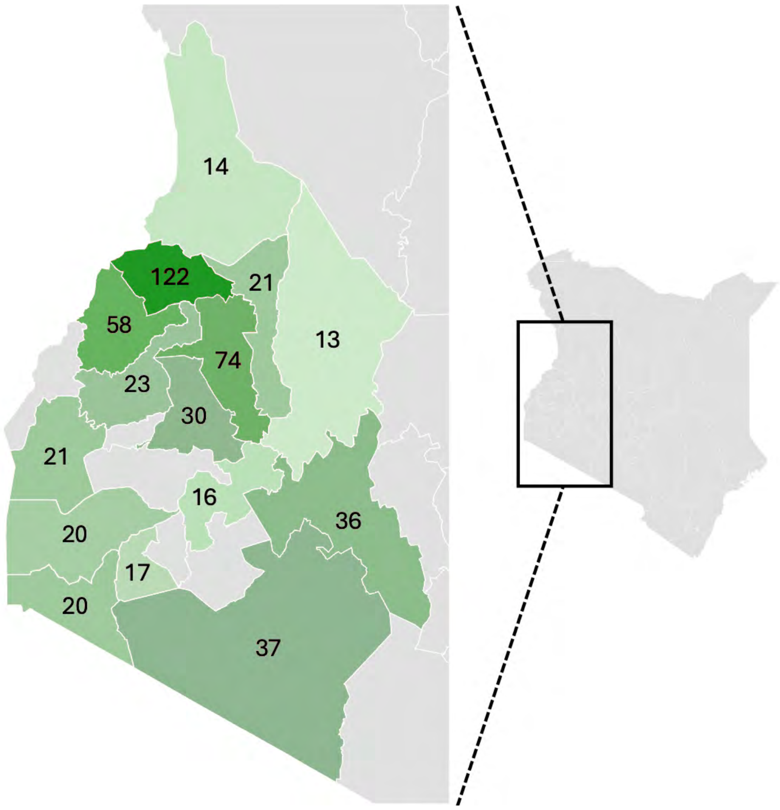
When repeating biochar input from maize residue for a second season, the cost of biochar input increases since more residue is available for processing. From this point, the financial outlook changes in favor of biochar due to legacy effect of amendments in the previous year which give incrementally higher grain output and is not the case with fertilizer. The difference in profit from biochar compared to synthetic fertilizer turns positive and would generate KES 83.4 million (US $ 0.64 million) more in the second season. At field level this translates to greater net earnings than synthetic fertilizer of KES 3,278 per acre in Trans Nzoia and KES 447 per acre in Kakamega. In a four-year period, biochar inputs from available maize residue would repay the lost profit and the cumulative net return would be KES 553 million (US $ 4.25 million) greater as compared to intensification with synthetic fertilizer.

Figure 4. Mitigation potentials of biochar amendment to maize croplands.



Climate mitigation

Figure 5. Added grain output through inter-county transfer of biochar in year five of implementation; expressed as x1,000 MT



Removal of CO_2 from the atmosphere through biochar inputs from available residues on maize croplands was simulated using a fixed C content of 55%, the lower end of reported values from informant #4 and literature. The conversion factor to CO_2 was 3.67 and a 100-year sequestration of 50% was included that from the long-term experiment by IITA. Taking all six counties with excess residue from maize, a total of 362,291 MT CO_2 would be removed in the first year of implementation (Figure 4). When compared to manufacturing emissions from synthetic fertilizer at 2.10 MT CO_2 per ton , the conversion of residue to biochar would compensate 172,848 MT of fertilizers. Official figures on fertilizer importation date back to 2021 and stood at a total 770,292 MT for all agricultural sectors. This would mean that biochar from maize residues in the six ranked counties would offset embodied carbon from roughly 22% of synthetic fertilizers used across the whole of Kenya. Increasing yield without additional fertilizer use also offsets the climate footprint of maize cultivation by 58,884 MT CO_2 in the first year, equivalent to the annual emission of 12,800 passenger vehicles. Within a span of four years, the cumulative climate mitigation effects from biochar use would amount to 2.23 million MT CO_2.

Alternate outcomes

The potential of biochar may be substantially lower or higher depending on specific factors of residue allometry and competing pulls which are bound to vary between counties and individual farms, unlike the modeled scenario where one mean value was used for all. Namely, if the harvest index for stover and shank are 10% smaller, and other scenario features kept constant, then Nandi County would not have excess residue, and 24% less biochar could be produced country-wide (273,158 MT). The total yield gain in this case would be 19% lower (122,971 MT) compared to the nominal modelled scenario and compensate 7% less of the drop in production since 2021. When the allocation to livestock is 5 MT per head of dairy and beef cattle, i.e., 50% of the total roughage required, and other scenario factors kept constant, the availability of excess residue is limited to Trans Nzoia County and Bungoma County, with a total biochar production of 106,916 MT. In this case, a total yield gain of 48,112 MT would be obtained, compensating 11% of the reduction in output since 2021. Under diminished biophysical potential the net revenue from biochar use remains financially attractive (KES 4,148 to KES 770 per acre). The lag time to reach a positive opportunity cost over use of synthetic fertilizer would be unchanged at one year, and initial foregone profit still recouped in a span of four years. In terms of climate mitigation, scenarios with lower resource availability would durably remove between 275,685 and 107,905 MT of CO_2 (17 to 7% of manufacturing footprint of fertilizer) and avoid 44,807 to 17,538 MT of embodied CO_2 emissions from fertilizer through higher use efficiency during the first year.

On the other hand, if the diversion of biomass to fodder would be 1 MT per head of dairy and beef representing 10% of required feed rate, and use of stover for mulching soil surface would be 0.4 MT per acre, equivalent to the recommended rate for 30% of cultivated area, then sufficient residue becomes available in Nandi County, Nakuru County, Kericho County and Kisii County for the practice to biophysically and financially viable. In this case, the total yield gain during the first cycle would be 275,439 MT which compensates for 61% of the output drop due to fertilizer crisis. Net profits from higher output would lay between KES 635 and KES 7,501 per acre, 1.5 to 40 times greater compared to the nominal scenario. There would be negative opportunity cost over use of fertilizer, except for Kericho County and Kisii County. By virtue of higher biochar input rates and yield gain, the foregone profit would be recouped in the third year. In terms of climate mitigation, greater resource availability would remove 610,378 MT of CO_2 (38% of manufacturing footprint of fertilizer) and avoid 100,403 MT of embodied CO_2 emissions from fertilizer through higher use efficiency in the first year.

National scale-up

In counties where no excess residue is available due to needs for animal fodder, soil surface cover and oil pressing, there is need to transfer resources from counties with high potential. This would be possible after four years for Trans Nzoia, Uasin Gishu and Bungoma Counties where biochar will have reached cumulative application rates of 3.2 to 1.7 MT per acre and higher grain yield levels can be maintained for another five years or more as shown by research. In these counties a total of 494,439

MT biochar is obtained which allows to amend 1.22 million acres of additional land at a dosage of 0.40 MT per acre. This area is equivalent to the entire maize cropland area of Nandi, Nakuru, Narok, Kericho, Migori, Siaya, West Pokot, Homa Bay and Kisii County, as well as 75% of Baringo County (Figure 5). This strategy would result in a total grain output increase of 522,190 MT or 5.80 million bags, which surpasses the drop in production from surges in fertilizer prices. In two years after that, the maize growing area in all other counties would have received the said dosage of biochar. Repeating this process combined with increased production of residue across cropland areas would build up biochar in the soil.

Operational considerations

Converting large quantities of biomass residue into biochar presents several logistical challenges and has a strong influence on the biophysical potential and financial viability of the practice. For one, distances between where resources are located, and the site of pyrolytic conversion need to be less than 0.5 kilometers else costs for transportation would become inhibitive. Preprocessing and pyrolysis systems must be capable of handling large volumes efficiently and with minimal labour requirement if 1.44 million MT of available residue is to be turned into biochar. This must take place within 1 month from harvest in the dry spell, so the biomass is in optimal condition, and to have biochar ready for the next planting season or for use to manage manure. So that service providers can work efficiently and maximize output they must have access to data tools for quantifying residue stocks based on geospatial information, crop growth simulation and farmer information. This way the movement of equipment and labour, as well as temporary storage, can be done timelier and at a lower cost. None of these aspects are unsurmountable as there is a broad range of existing solutions which can be adapted and integrated for biochar production at scale.

When it comes to pyrolysis equipment, simple dug pits have the lowest threshold and cost but require substantial labour and land, hence these are limited to small-scale production by farmers themselves. Conical kilns made of metal sheet are easy to move, making them suitable for hard-to-reach areas but are restrictive in terms of labour inputs and output capacity. Based on a daily production volume of 180kg biochar for these systems, as referenced from informant #3 and #4, it would take 20,773 units and 51,934 staff a period of three months to process available residue under the nominal production and allocation scenario. At a price tag of KES 26,000 (US $ 200) this approach would have a total capital cost of KES 540 million (US $ 4.15 million). Moving up the technology ladder, there are automated systems that can be moved between sites, require less labour and have less power needs. With outputs of 0.45 to 1 MT biochar per day, it would take between 3,739 and 8,309 units and 5,608 staff a period of three months to process available residue under the nominal production and allocation scenario. At price tags of KES 0.9 to 6.5 million (US $ 7,000 to $ 50,000), this approach would require a total capital cost of KES 7.5 to 24 billion (US $ 26 to $ 187 million).

How greater accuracy can be obtained

While this assessment demonstrated how biochar from maize residue can help Kenya alleviate food shortages and fertilizer price surges in the short run, there are several aspects of the modeling that must be refined to provide more accurate guidance of investments and policies.

- Biomass stocks: Mine datasets from agricultural agencies and survey livestock owners and farmers to understand quantities of maize residue used for animal fodder, mulch and oil press, now and in future, so calculations on availability better reflect actual context.
- Yield responses: Utilize geospatially explicit and mechanistic modeling to obtain more precise figures on how biochar will increase crop yields in each county, including coefficient adjustments for drought and heat on nutrient use efficiency for assessing outcomes under varying conditions.
- Fertilizer dynamics: Integrate existing frameworks that evaluate fertilizer price and elasticity effects on input use and efficiency in farming systems to identify counties and contexts where biochar can be applied best to cushion cost increase and suboptimal nutrient uptake.
- Climate mitigation: Run model with process-based carbon sequestration simulator and county-specific emissions from fertilizer use so removals and offset can be disaggregating to finer geographical units and trends over different seasons and years understood.
- Associated costs: Factor in a broader range of production costs, market demand and carbon credit values to determine the preconditions for financial viability of service provision and farmer adoption.

Key informants

Reference data for the assessment was gathered through key informants from various national and international organizations that are knowledgeable of Kenya's farming system and deployment of biochar production. The selection of informants was made based on knowledge of authors and review of public information, and comprised of governmental agencies, research institutes and delivery. Questions were aimed at identifying data on biophysical resources and associated costs, as well as more broadly, the past and current trends of fertilizer and biochar inputs for maize cropping systems. #

Table 2

	Organization	Information
1.	Council of Governors https://www.cog.go.ke	Official statistics on maize production, achieved number of 90 kg bags and harvested area, for each specific county
2.	International Livestock Research Institute https://www.ilri.org	Inventory of livestock numbers per county; Quantity and formulation of feed per head of cattle
3.	PlantVillage Kenya https://plantvillage.psu.edu	Biochar recovery and fixed carbon for maize residue; Cost of production for biochar and incomes from carbon credit issuance
4.	BiocharLife https://www.biochar.life	Biochar recovery and fixed carbon for maize residue; Market prices of biochar on voluntary market and costs of monitoring, reporting and verification; Internationally recognized safety margins applied for calculation of durable removal
5.	Kiplombe Farm	Residue usage for livestock, manure management and soil cover in large-scale cultivation system

Candidate biomass resources

Residues from other food crops are suitable and attractive for biochar production. The principal rule is that resources must have a carbon to nitrogen ratio greater than 25, which excludes food waste, animal manure and stover from most legumes. Such resources are better composted and are operationally less favorable for pyrolysis. In Kenya the main biomass caches with potential are sugarcane bagasse, (diseased) cassava stems, rice husk, coconut shells, coffee husks, wheat straw, peanut shells, and pineapple trash. Sources also exist in non-food agricultural systems such as from sisal fiber production, next to pastoral, urban and even aquatic ecosystems including invasive Prosopis shrubs, yard trimmings, water hyacinth, and agroforestry systems like bamboo.

Annex

#1. Overview of factors used in calculating the potential biochar output, yield benefit and climate mitigation for the mean and alternate scenarios.

Parameter	Mean	Alternates
Harvest ratio stover:grain	2.217	10% less
Harvest ratio shank:grain	0.565	10% less
Non-removable fraction for stover and shank	0.5	NA
Stover for dairy and beef cattle feed (MT per head per year)	2	5 and 1
Stover for boran feed (MT per head per year)	0.5	NA
Proportion of shank to oil press and/or compost	50%	NA
Stover use for mulching soil surface (MT per acre)	0.61	0.4
Biochar recovery rate for stover and shank	25%	NA
Yield response (MT grain added per MT biochar per acre)	0.18	NA
Retail price of biochar (KES per MT)	12,000	NA
Retail value of maize grain (KES per 90 kg)	4,000	NA
N fertilizer to increase grain yield by 0.4 MT per acre (kg)	40	NA
Retail price of fertilizer (KES per 50 kg)	6,500	NA
Fixed carbon content of biochar	55%	NA
C to CO_2 conversion	3.67	NA
100 year retention of biochar caron in soil	50%	NA

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