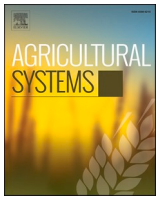
Agricultural Systems 212 (2023) 103754



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Agricultural Systems

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Modelling the effects of soil organic content and pH on the yield responses of tea to nitrogen fertilizer

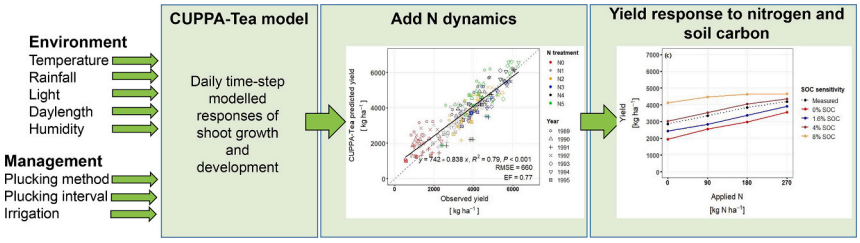
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HIGHLIGHTS

- N dynamics, including the effects of soil organic content and pH, were developed and incorporated into the CUPPA-Tea model.
- The resulting model explained 79% of the variation in tea yields from experiments in Tanzania and Kenya.
- Under no N fertilizer, the model predicted greater yields in a site with a high rather than a low soil organic content.
- Minimal N losses due to volatilisation, denitrification, and leaching were predicted (at pH 4.0–4.5 and rooting depths 3–5 m)
- CUPPA-Tea was also used to identify the financially optimum N fertilizer application rate in pruned and unpruned tea.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Kairsty Topp

Keywords:
CUPPA-tea
Nitrification
Denitrification
Mineralization
Soil organic matter
N response

ABSTRACT

CONTEXT: Sustained high yields of tea rely on the supply of nitrogen (N) from soil reserves, typically maintained by N fertilisation from inorganic or organic sources.
OBJECTIVE: This paper describes how soil N levels, including the effects of soil organic content and pH, were developed and incorporated into a crop yield simulation model called CUPPA-Tea.
METHODS: The nitrogen dynamics are presented in terms of i) the initial nitrogen stocks, ii) the addition of nitrogen to the system, iii) the uptake, use and loss of nitrogen by tea plants, and iv) nitrogen flows within the soil. CUPPA-Tea was then calibrated and validated using measured tea yields from Tanzania and Kenya.
RESULTS AND CONCLUSIONS: After integrating a wide range of nitrogen algorithms, the model explained 79% of the variation in annual yields within a nitrogen and irrigation experiment in Tanzania and a fertilizer experiment in Kenya. The slope of the relationship was 0.84 and 0.73 respectively, the root mean square error was 660 kg ha^{-1} and 507 kg ha^{-1}, and the modelling efficiency was 0.77 and 0.75 respectively. The model predicted that in the absence of N application, tea yields would be higher from a site with a high rather than a low soil organic content. By contrast, at high levels of mineral N application, the yield response in the model was

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https://doi.org/10.1016/j.agsy.2023.103754
Received 16 April 2023; Received in revised form 21 August 2023; Accepted 25 August 2023
Available online 8 September 2023
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not sensitive to the soil organic content. Hence within the model, a site in Tanzania with a low soil organic content of 1.6% showed a greater yield response to applied mineral N than a site in Kenya where the soil organic carbon was 4.0%. The model also predicted small losses of N from the cropping system through denitrification and leaching due to the acidic soil conditions (pH < 4.5) and an assumed tea rooting depth between 300 and 500 cm. In Tanzania, irrigation was predicted to result in around 10% higher nitrogen uptake than under unirrigated conditions.

SIGNIFICANCE: The use of the CUPPA-Tea model can be useful in supporting decision making and improving the accuracy of tea yield estimates, as well as predictions of N fate within the soil-plant-atmosphere continuum.

1. Introduction

Tea is a widely consumed beverage produced from young tender shoots harvested from tea plants (*Camellia sinensis* (*L.*). The largest areas of tea are found in China, India, Kenya, and Sri Lanka, with Kenya being the largest exporter of tea (FAO, 2022). Although Kenya dominates tea production in Africa, there is also significant tea production in Uganda, Malawi, Tanzania, Rwanda, and Burundi (FAO, 2022). During the main growing seasons, tea shoots in East and Central Africa are typically harvested at intervals ranging from 7 to 18 days, making tea one of the most intensively managed crops. Because the harvested product is tender growing shoots, tea yields are particularly sensitive to nutrient and water stress. Hence optimum management of nutrients and water is critical to maximise the profitability of tea production.

Computer-based crop simulation models are a way of collating quantitative knowledge about how the development and growth of crops interact with their environment (Asseng et al., 2014). They can also provide managers with insights into how changes in temperature, daylength, drought stress, and harvesting practice will affect crop yields and quality (Matthews and Stephens, 1998a; Giannitsopoulos et al., 2021). For these reasons together with the greater availability of digital data, there is increasing interest in using crop models for research, education and extension, and guiding decision making in businesses (Hoogenboom et al., 2020).

Regression models have been used to predict the effect of climate on annual tea yields, for example in China (Boehm et al., 2016), Assam (Rao et al., 2007) and Kenya (Sitienei et al., 2017). Beringer et al. (2020) demonstrated the use of a bio-physical source-limited model to describe the effect of climate change on annual tea yields at a global scale. However, there are very few models that simulate the growth of individual tea shoots. Fordham and Palmer-Jones (1977) described a tea shoot growth model, developed in Malawi, to explain the peaks and throughs in tea production because of the synchronous growth of shoots following a period of dormancy and/or dry weather. Eitzinger and Anandacoomaraswamy (1997) described a daily time step model which simulated shoot growth and yields in Sri Lanka. The focus of this study is a very detailed model that simulates tea shoot development and growth called CUPPA-Tea, based on experimental work in Tanzania (Matthews and Stephens, 1998a, 1998b). The model operates on a daily time step and includes routines describing shoot growth and development, dry matter production and partitioning and the crop water balance (Matthews and Stephens, 1996). It has previously been tested in Tanzania (Matthews and Stephens, 1998b) and in north-east India (Panda et al., 2003), accounting for the effect of drought stress and a range of irrigation levels.

In Kenya, the application of nitrogen (N) fertilizer is one of the most expensive aspects of tea production (Omollo, 2010). Under suitable conditions, N application can have large positive effects on tea yields (Zhang et al., 2021), because of the need to replace the N lost from the field in the harvested crop. In Kenya, moderate N applications have also been shown to increase caffeine formation, but to decrease the flavour of black tea (Owuor et al., 1991). However, to our knowledge, there is currently no process-based tea model that simulates the effect of nitrogen on tea yields. Hence, this study describes the inclusion of nitrogen algorithms into the CUPPA-Tea model, presents its calibration and validation using measured tea yields in Tanzania and Kenya, illustrates the nitrogen balance for both experiments, and depicts how different levels of soil organic carbon, affect tea yield at different amounts of nitrogen fertilizer.

2. Methodology

2.1. Model development

CUPPA-Tea is a daily time-step model that simulates the development and growth of individual tea shoots in response to temperature and photoperiod (Matthews and Stephens, 1998a), and drought (Matthews and Stephens, 1998b). The input parameters include daily weather, soil parameters, irrigation regimes (if relevant), details of tea plant spacing, and tea cultivar characteristics. The major outputs of the model include descriptions of shoot development and growth, the numbers and dry yields of harvested shoots, and descriptions of results on water and nitrogen dynamics. The source code of CUPPA-Tea was originally written in Turbo Pascal v7.0 (for DOS) and was designed to be compatible with the standards defined by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project (Hunt, 1994). In 2016, the CUPPA-Tea model was translated into the object-oriented programming language C# (Holden et al., 2016). A commercial cloud-based version of the model (also in C#) was also developed in collaboration with Microsoft in 2018, using daily data regarding the weather and actual harvest dates. During the translation of CUPPA-Tea, additional algorithms were added to include the effect of pruning.

In the original CUPPA-Tea algorithms, Matthews had implemented draft coding for nitrogen, but the algorithms were not calibrated or validated. The broad approach for describing nitrogen dynamics was based on the algorithms in the CERES-Maize model described by Godwin and Jones (1991). In 2020, work started on using the nitrogen algorithms and calibrating the results against historic field measurements. The nitrogen dynamics require an understanding of i) the initial nitrogen stocks, ii) the addition of nitrogen to the system, iii) the uptake, use and loss of nitrogen by tea plants, and iv) nitrogen dynamics in the soil. A top-level diagram illustrating the overview of the CUPPA-Tea model is presented in Annex A-Fig. A1.

2.2. Initial nitrogen stock

The model assumes initial nitrogen stocks comprising nitrogen held as plant tissue, soil inorganic nitrogen, and soil organic nitrogen. The initial level of soil inorganic nitrogen, as NO_3^- and NH_4^+ (mg kg^{-1} of soil) are specified for depths of 15, 50, 200, 320, and 500 cm (Annex A-Table A3). The initial level of organic carbon is also specified for similar depth increments. For the crop residue on soil surface, the model assumes an initial C:N ratio of 40:1 and an initial weight of 1000 g m^{-2}. It also assumes an initial above-ground biomass of the canopy in terms of stem wood (2325 g m^{-2}) and green stems (200 g m^{-2}). This is multiplied by an initial assumed canopy N fraction of 0.0325 to give an initial canopy nitrogen value of 114 g N m^{-2}. The model assumes an initial thick root weight of 1245 g m^{-2}, a fine root weight of 190 g m^{-2}, and a root residue weight (dead root weight) of 200 g m^{-2}. Assuming a proportion of nitrogen in the root of 0.01, these values result in value of 16

g N m^{-2}. Hence the initial plant nitrogen content is about 130 g N m^{-2}, i.e., 1300 kg N ha^{-1}.

2.3. Addition of nitrogen to system

Additional nitrogen to the crop system can be added as mineral or organic fertilizer to the surface of the uppermost layer of the soil. In the model, it is assumed that nitrogen held in the form of nitrate and urea can move through the soil with the movement of water from upper to lower soil layers; ammonium is assumed not to be transported (Ritchie, 1985; Godwin and Jones, 1991). The model includes the capacity to include nitrogen from atmospheric deposition, but due to a lack of real measurements no N deposition was assumed. Previous studies have also indicated that N deposition tends to be minimal at between 2.2 and 10.3 kg N ha^{-1} yr^{-1} (Laouali et al., 2016; Bakayoko et al., 2021). The model calculates a dynamic C: N ratio (*cnr*) (Eq. 1) of the carbon as litter and dead roots relative to the available inorganic nitrogen in those residues. The carbon is calculated from the new organic matter pool (OM_{new}) multiplied by a carbon fraction ($Cfrac_{new}$; 0.4) divided by the new organic N pool ($OrgN_{new}$; kg N ha^{-1}) plus the sum of ammonium and nitrate in the soil (*Ntot*; kg N ha^{-1}; Eq. 1). Carbon pools are updated daily in OM_{new} by accumulating the quantity of each pool (carbohydrate, cellulose and lignin) per soil layer (i).

$$cnr = \frac{OM_{new[i]} * Cfrac_{new}}{OrgN_{new[i]} + Ntot} \tag{1}$$

For fresh organic matter the assumed N fraction is 0.02. The value of 0.02 is the product of the fraction of C in the fresh organic matter (40%), the biological efficiency of C turnover by the microbes (40%) and the N: C ratio of the microbes (0.125: 1) (Godwin and Jones, 1991). For humus the C and N fractions are 0.4 and 0.024 respectively (Moran et al., 2005).

2.4. Uptake, use and loss of nitrogen by the crop

The model assumes that the crop can only take up N in the form of inorganic ammonium (NH_4^+) and nitrate (NO_3^-) ions. It is assumed that quantity of N taken up is either constrained by the crop N demand or the N supply. The demand for N has two components: the demand by the existing canopy and roots, and the demand for canopy or root growth. The demand from the canopy is calculated as the product of the canopy weight (W_{canopy}) and the difference between a critical N level for the canopy (*CCNP;* default value: 0.04) and the actual proportion of N in the canopy (*CANC*) (Eq. 2). A similar relationship exists for the roots based on critical N level in the roots (*RCNP*) and the actual proportion of N in the roots (*RANC*) (Eq. 3). The demand for N for new canopy growth (*NewCanopyDem*) depends on the potential growth rate of the canopy and the value of *CCNP* (Eq. 4), and a similar relationship was assumed for the roots (Eq. 5). The summation of all demands determines the total crop N demand (Eq. 6).

$$CanopyDem = W_{canopy} * (CCNP - CANC) \tag{2}$$

$$RootDem = W_{root} * (RCNP - RANC) \tag{3}$$

$$NewCanopyDem = PotCanopyGrowth * CCNP \tag{4}$$

$$NewRootDem = PotRootGrowth * RCNP \tag{5}$$

$$TotCropNDem = CanopyDem + RootDem + NewCanopyDem + NewRootDem \tag{6}$$

The potential N uptake across the soil profile (Tot*PotNUpt*) is calculated by adding up the potential uptake of NH_4^+ and NO_3^- (Eq. 7 and 8). At each soil layer ($Layer_{[i]}$), this is determined by the maximum daily uptake of NH_4^+ and NO_3^- per unit length of root (which is assumed to be 0.006 mg N (cm root)$^{-1}$), the rooting density (*RLv*[i]; cm root (cm^3 soil)$^{-1}$), the availability of NH_4^+ and NO_3^-, and the soil-water status. The availability factors fNH_4 and fNO_3 range from 0 to 1 (Eq. 9; Eq. 10) and are dependent on the soil NH_4^+ and NO_3^- concentration (mg kg^{-1} soil).

$$PotNH_4Upt = 0.006 * 100 * RLv_{[i]} * Layer_{[i]} * fNH_4 * smdfr^2 \tag{7}$$

$$PotNO_3Upt = 0.006 * 100 * RLv_{[i]} * Layer_{[i]} * fNO_3 * smdfr^2 \tag{8}$$

$$fNH_4 = 1.0 - exp\left(-0.03 * [NH_4]_{[i]}\right) \tag{9}$$

$$fNO_3 = 1.0 - exp\left(-0.03 * [NO_3]_{[i]}\right) \tag{10}$$

A zero to unity soil-water factor (*smdfr*) reduces the potential N uptake as calculated from the relative availability of soil water (Eq. 11; Eq. 12), where *sat*, *swc*, *Dul* and *LL* (all in units of cm^3 cm^{-3}) correspond to the water content at saturation, the actual soil water content, the drained upper limit, and the lower limit at soil layer [i] respectively. In a situation where the potential N supply (*PotNSup defined as the sum of PotNH4Upt and PotNO3Upt)* is greater than the *TotCropNDem*, an *NUF* factor is used (Eq. 13) to reduce the N uptake from each layer to the level of demand.

$$smdfr = \frac{sat_{[i]} - swc_{[i]}}{sat_{[i]} - Dul_{[i]}}, \quad if\ swc[i] > Dul[i] \tag{11}$$

$$smdfr = \frac{sat_{[i]} - LL_{[i]}}{Dul_{[i]} - LL_{[i]}}, \quad if\ swc[i] < Dul[i] \tag{12}$$

$$NUF = \frac{TotCropNDem}{TotPotNSup} \tag{13}$$

The effect of nitrogen on plant growth is related to a nitrogen deficiency index (*Nfac*), which typically ranges between 0 and 1, and is dependent on the actual proportion of N in the canopy (*CANC*), *CCNP* below which growth will be reduced, and a minimum N content (*CMNC* default value: 0.01) below which N content never falls (Eq. 14).

$$Nfac = \frac{CCNP - CANC}{CCNP - CMNC} \tag{14}$$

It was assumed that nitrogen stress can reduce both dry matter production and the rate of leaf area expansion and leaf senescence. The rate of dry matter production by the crop (*DMP*; kg DM ha^{-1} d^{-1}; Eq. 16) is determined as a function of the potential crop growth rate (PCGR; kg DM ha^{-1} d^{-1}; Eq. 15), a temperature factor (*Tfac*), and the minimum of either a water stress multiplier (*swdf1;* calculated from the water stress factor) or the value of *Ndef*1, where the value of *Ndef*1 is defined by Eq. 17. In Eq. 15, *S* refers to solar radiation (MJ ha^{-1}), *RUE* to radiation use efficiency (g MJ^{-1}), *kext* to extinction coefficient, and *LAI* to leaf area index (m^2 m^{-2}).

$$PCGR = S * RUE * (1 - exp(-kext * LAI)) \tag{15}$$

$$DMP = PCGR * Tfac * Min(swdf1, Ndef1) \tag{16}$$

$$Ndef1 = 0.9952 * Nfac^2 - 0.0354 * Nfac + 0.252 \tag{17}$$

The relationship between *Ndef*1 and the nitrogen deficiency index (*Nfac*) was based on a curvi-linear response described by Godwin and Jones (1991). However, a y-axis intercept of 0.252 was added to ensure that dry matter production could still be positive following prune events even if no nitrogen was applied.

The nitrogen deficiency index was also used to modify the potential growth of leaves in terms of its effect on leaf area expansion and leaf senescence. The rate of leaf extension (*LeafLength*; cm d^{-1}) depends on the shoot extension rate (*S2ER*), co-efficients for the temperature in day degrees (*DDllen*; values from 0 to 1), day length (*DLfac*; values from 0 to 1) and the minimum of co-efficients related to the saturation deficit (*SDfac*), a water stress reduction factor (*SERwf*) and the nitrogen deficiency index (*Nfac*) (Eq. 18). A similar relationship is also assumed for

leaf area growth rate (Eq. 19), where *PotLeafArea* refers to the potential leaf area.

$$LeafLength = S2ER*DDIlen*DLfac*Min(SDfac, Min(SERwf, Nfac) \quad (18)$$

$$LeafAgr = PotLeafArea*DDIlen*DLfac*Min(SDfac, Min(SERwf, Nfac) \quad (19)$$

Lastly, we assumed that nitrogen could be lost from the tea plant in four main ways. Firstly, N can be lost from the system as harvested leaf. Crop N can also be lost from the abscission of mature leaves and through pruning. The canopy N fraction is calculated daily as the quotient of the canopy N content and the canopy weight. On dates when the tea is pruned, the pruned canopy and the associated nitrogen is assumed to be added to the topsoil, with the carbon and nitrogen added to fresh organic matter and organic N pool respectively. Lastly crop N can be lost through root exudation, but the organic N is added back to the fresh organic matter pool where it can be mineralized and made available to the plant again.

2.5. Nitrogen flows within the soil

The N flows within the soil were considered in terms of mineralization, nitrification, denitrification, volatilisation, and leaching (Fig. 1). CUPPA-Tea works with a user-defined number of soil layers, whose thickness depends on the total soil depth. The default number of soil layers is 20, which for instance corresponds to a thickness of 15 cm when soil depth is 300 cm.

2.5.1. Mineralization

The conversion of soil organic N to inorganic N in CUPPA-Tea occurs through mineralization of four organic matter pools (*OMPools*) (Eq. 20). The pools comprise fresh organic matter (FOM) (which is further subdivided into carbohydrate, cellulose and lignin) and the more stable humus (HUM). For each component of the pool there is a specified decay constant (*rdecr*; Eq. 20; units: d^{-1}) which is 0.2, 0.05 and 0.0095 for carbohydrate, cellulose and lignin respectively (Seligman and Van, 1981). Mineralization is also modified by a soil water factor (Moisture factor-*mf*; Fig. 4a), a C: N ratio factor (*cnrf*; Fig. 2a) and a soil temperature factor (*Tf*; Fig. 2b). For the humus, which is more resistant to decay, the potential decay rate constant is small ($8.3*10^{-5}$ d^{-1}). This is adjusted by *Tf* and *mf* also, but *cnrf* is not used. Although not used in this study, another index (*HumMinFactor*) is used to adjust the humus mineralization rate for atypical soils such as some volcanic ash soils where mineralization is low, and on some freshly cultivated virgin soils where mineralization is high).

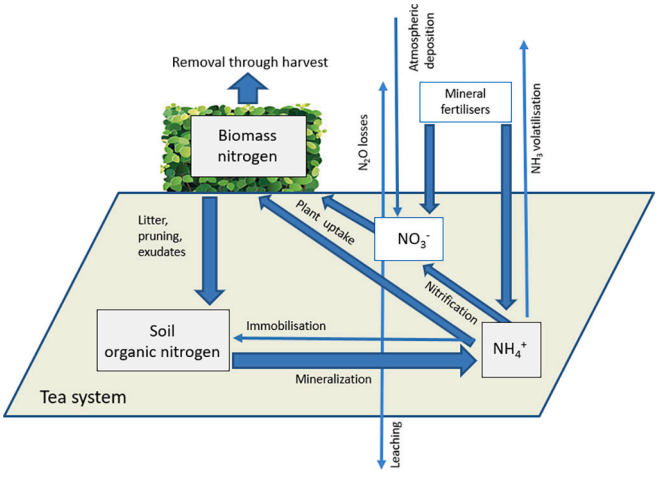


Fig. 1. Schematic diagram showing the main stocks and flows of nitrogen between the soil and the tea crop.

The mineralization rate of the current day ($N_{mineralise[t+1]}$) is computed as the sum of the mineralization rate of the previous day and the product of the new organic N (*OrgN*$_{new}$; kg ha^{-1}) and the fraction of organic matter pools from the total organic matter and the reduction factors (with *i* indicating the type of pool; Eq. 20). The level of *OrgN*$_{new}$ is updated daily as the sum of immobilized NH_4^+ and NO_3^-, minus $N_{mineralise}$ and the new humus N (Eq. 21), assuming that 20% of N released from the new organic matter is added to the humus.

$$N_{mineralise[t+1]} = N_{mineralise[t]} + OrgN_{new} * \left(\frac{OMPools_{[i]}}{TotOM}\right) * Tf * mf * cnrf * rdecr_{[i]} \quad (20)$$

$$OrgN_{new} = N_{imm}NH_4 + N_{imm}NO_3 - N_{mineralise} - HumusN_{new} \quad (21)$$

It is assumed that the N requirement for microbial decay of a unit of new organic matter is 0.02 (Eq. 22; where *TotAvailN* is the sum of NH_4^+ and NO_3^- and *Grcom* (Eq. 23) refers to cumulative organic matter mineralization estimated as the product of the organic matter pools, the reduction factors and the decay rates (Eq. 24). Each day, a quantity of immobilized N (N_{imm}; kg ha^{-1}) is derived first from the NH_4^+ pool ($N_{imm}NH_4$; Eq. 25) above a minimum level of 0.5 mg NH_4^+ (kg soil)$^{-1}$, then taken from the NO_3^- pool ($N_{imm}NO_3$; Eq. 26) down to the minimum level (min NO_3^- concentration: 0.25 mg kg^{-1} soil).

$$N_{imm} = \text{limit}(\text{Grcom}*(0.02 - OrgN_{new}/\text{TotOM}), 0, \text{TotAvailN}) \quad (22)$$

$$Grcom_{[t+1]} = Grcom_{[t]} + loss \quad (23)$$

$$loss = OMPools_{[i]} * Tf * mf * cnrf * rdecr_{[i]} \quad (24)$$

$$N_{imm}NH_4 = Max(0, Min(N_{imm}, \text{NH}_4 - \text{NH}_4 min)) \quad (25)$$

$$N_{imm}NO_3 = Max(0, Min(N_{imm}, \text{NO}_3 - \text{NO}_3 min)) \quad (26)$$

2.5.2. Nitrification

Nitrification is the process of biological oxidation of NH_4^+ to NO_2^- to NO_3^- that can occur under aerobic conditions, and it was assumed to be affected by the substrate NH_4^+, oxygen, soil pH, and temperature. An environmental limit for nitrification (*Elnc*) was determined from the minimum of a temperature factor for mineralization (*Tf*), a soil water factor for nitrification (*wfd*; Fig. 4a) and a factor *Sanc* (Eq. 27). The soil water factor for nitrification increases from 0 at permanent wilting point to 0.9 at field capacity and then decreases to 0 at saturation (Fig. 4a). The factor *Sanc*, ranging from 0 to 1, is related to the ammonium pool (*sNH*$_4$; kg ha^{-1}) (Eq. 28).

$$Elnc = Min(Tf, wfd, Sanc) \quad (27)$$

$$Sanc = 1 - exp(-0.01363*\text{sNH}_4) \quad (28)$$

The potential nitrification rate (*PotNitrR*; kg N ha^{-1} d^{-1}) is derived from a Michaelis-Menten kinetic function dependent only on ammonium (Eq. 29; McLaren, 1970). The assumption is that a maximum of 80% of the ammonium pool can be nitrified in one day (Li et al., 2018), where *NH*$_4$ and *sNH*$_4$ is the ammonium concentration (mg kg^{-1} soil) and ammonium pool (kg ha^{-1}) respectively.

$$PotNitrR = Min\left(40*\frac{\text{NH}_4}{\text{NH}_4 + 90}, 0.8\right)*\text{sNH}_4 \quad (29)$$

The daily nitrification rate ($N_{nitrify}$; kg N ha^{-1} d^{-1}) is determined (Eq. 30) as the minimum between the product of *PotNitrR* and the value of *a*, and *b2* which is the NH_4^+ available above the minimum (0.5 mg kg^{-1} soil). The value of *a* (Eq. 32) is determined by the minimum of a series of 0 to 1 environmental indices related to pH (Fig. 3a), temperature (Fig. 3b), soil water content (Fig. 4a) and *rp2*. The assumption in CUPPA-Tea is that there is no nitrification at pH lower or equal to 4.5 and greater or equal to 9.0 and at soil temperatures lower than 5 °C (Yao et al.,

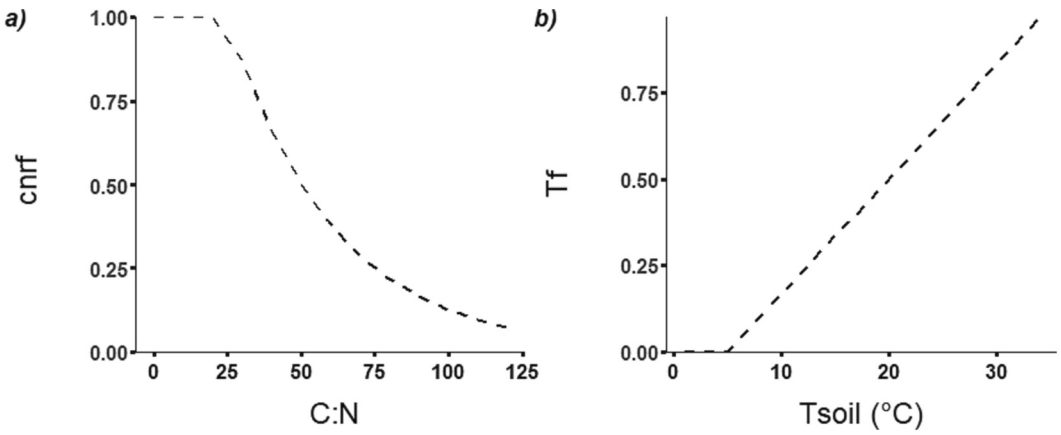


Fig. 2. Response of a) the C:N ratio factor (*cnrf*) to the soil C: N ratio, and b) the soil temperature factor (*Tf*) to soil temperature (T_{soil}) assumed in the CUPPA-Tea mineralization routine.

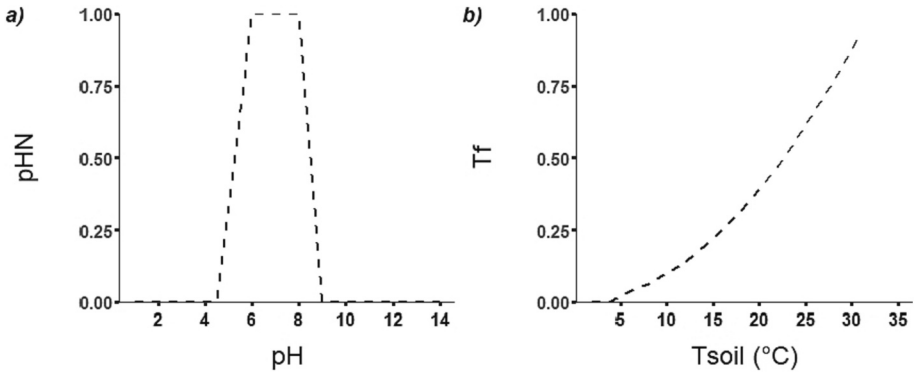


Fig. 3. Response of a) a pH factor (*pHN*) to pH and b) a soil temperature factor (*Tf*) to temperature in the CUPPA-Tea nitrification routine.

2011). The value of *rp2* is included to account for reductions in nitrification which can occur if conditions in the immediate past (last 2 days) were unfavorable for nitrification. As shown in Eq. 31, this was assumed to be dependent on *Elnc* and the previous day's relative microbial nitrification potential in the layer (*cni*) which assumed to have an initial value of 0.1.

$$N_{nitrify} = Min(PotNitrR^{*}a, b2) \quad (30)$$

$$rp2 = cni^{*}exp(2.302^{*}Elnc) \quad (31)$$

$$a = Min(rp2, wfd, Tf, pHN) \quad (32)$$

Calculations are carried out for the current day, the day before and the day after. *Sarnc* is a 0 to 1 factor for ammonium availability (Eq. 33). The least limiting of the current day's and the previous day's water (*wfd* and *wfy* respectively) and temperature factors (*Tf* and *Tfy* respectively) are used in the calculation of the new value of *cni* (Eq. 34–36).

$$Sarnc = 1 - exp(-0.1363^{*}\mathrm{sNH_4}) \quad (33)$$

$$xw = Max(wfd, wfy) \quad (34)$$

$$xt = Max(Tf, Tfy) \quad (35)$$

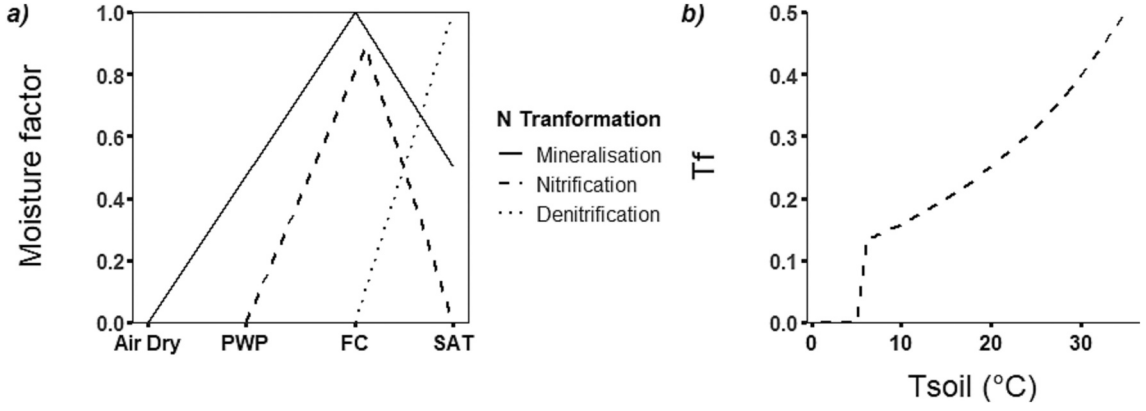


Fig. 4. a) Soil water indices used in CUPPA-Tea to modify soil N transformation rates (PWP: permanent wilting point, FC: field capacity, SAT: saturation moisture content, (adapted from Godwin and Jones, 1991) and b) soil temperature factor response used in CUPPA-Tea denitrification routine.

$$cni = rp2*Min(xw, xt, Sarnc) \quad (36)$$

An effect of the above, is to moderate the effect of a single day of low soil temperature or drought stress on the value of microbial nitrification potential (*cni*). The relative magnitudes of *exp(2.302*Elnc)* and *Min(xw, xt, Sarnc)* determine whether relative nitrification potential increases or decreases over the short term (Godwin and Jones, 1991).

In nitrification, most of the oxidized ammonium is turned into nitrate (NO_3^-) via nitrite (NO_2^-), and a small proportion of nitrogen can be released as N_2O. The fraction of nitrification associated N_2O emission has been modelled as 0.5% in the ExpertN model and 2% in the CENTURY model (Frolking et al., 1998). Within CUPPA-Tea, we assumed a loss of 1% of gross nitrification as used in the VISIT model (Inatomi et al., 2019).

2.5.3. Denitrification

Denitrification refers to the reduction of nitrate to gaseous products such as NO, N_2O and N_2. Parton et al. (2001) reported that denitrification typically occurs when the water-filled pore space is above 55%, reaching a maximum when the soil is saturated and soil bacteria use nitrate as an oxygen source. Hence CUPPA-Tea assumes denitrification when the soil water content exceeds field capacity (Fig. 4a), soil temperature is >5 °C (Fig. 4b), and a nitrate concentration is >1 mg NO_3 kg^{-1} soil. In the model, the daily denitrification rate ($N_{denitrify}$; kg N ha^{-1}) is assumed to be 0.000006 kg N ha^{-1} multiplied by a function of a water factor (Fig. 4a), a temperature factor (Fig. 4b), the nitrate concentration NO_3^- (mg kg^{-1} soil) and the total water extractable carbon (*cw*; mg C kg^{-1} soil) (Eq. 37). The value of *cw* is calculated 24.5 mg (kg soil)$^{-1}$ plus 0.31% of the soil carbon (*SoilC;* kg ha^{-1}) (assumed to be 58% of stable humic fraction), plus the C content of carbohydrate fraction (*OMpools*[1]) of any new organic matter pool ($Cfrac_{New}$ assumed to be 0.4; Eq. 38; Rolston et al. (1980)).

$$N_{denitrify} = 6*10^{-6}*fw*Tf*NO_3*cw \quad (37)$$

$$cw = 24.5 + (SoilC*0.0031 + Cfrac_{New}*OMpools[1]) \quad (38)$$

2.5.4. Volatilisation

The volatilisation routine was based on an approach described by Liu et al. (2020) and is used in the DNDC model. Ammonia (NH_3) volatilisation to the atmosphere is derived from the ammonia concentration in soil water $NH_3(l)$ which is dependent on the ammonium concentration [NH_4^+], the pH, and the temperature (Eq. 39).

$$[NH_3(l)] = \frac{1.945\ e^{0.0645\ T}*10^{-15}*[NH_{4^+}]}{(1.416 + 0.01357\ T)*10^{-5}*10^{-pH}} \quad (39)$$

The daily emitted flux of the gas phase NH_3 (Eq. 40; kg N ha^{-1}) is then calculated as:

$$\mathrm{Flux}(NH_3) = NH_3(l)*fwind*ftemp*fdepth \quad (40)$$

where *fwind* is a function of the wind speed (Eq. 41; wind, within the volatilisation, currently assumed to be constant: 2 m s^{-1}), and *ftemp* is a function of soil temperature (T_{soil}; °C) (Eq. 42). There is also a soil depth function (*fdepth*) where *q* is the number of soil layers and j is the layer of application which is assumed to be 0 as fertilizer is applied to the soil surface (Eq. 43).

$$fwind = 0.1 + \frac{(1.5*\mathrm{wind})}{(1 + \mathrm{wind})} \quad (41)$$

$$ftemp = 0.1 + \frac{(2*T_{soil})}{(45 + T_{soil})} \quad (42)$$

$$fdepth = \frac{(q - j)}{q} \quad (43)$$

2.5.5. Nitrate flux

Within the soil, only the movement of nitrate and urea were considered; ammonium is assumed not to be transported as it is retained by the clay component of the soil (Table 1). Movement of nitrate and urea, assumed to be dependent on water movement from one layer to the next, was calculated using the same cascading approach where N lost from one layer is added to the one below. A fraction of the mass of nitrate (sNO_3) present in each layer is assumed to move with each drainage event. Within the water routine of the model (Matthews and Stephens, 1998b), water volume moving from layer (*L*) to the layer below ($FLUX_{[L]}$) is calculated. Prior to drainage, the volume of water present in each layer ($swc_{[i]} * Layer_{[i]}$) and the water draining from each layer ($FLUX_{[L]}$) in the profile is used to calculate the nitrate lost from each layer (*OutN*; Eq. 44). When NO_3^- concentration falls to 1 mg kg^{-1} no further leaching from that layer is assumed. Nitrate moving from a layer (*UpN*) is calculated as a function of upward movement ($FLOW_{[L]}$) in a manner identical to leaching (Eq. 45).

$$OutN = sNO_3*\frac{FLUX_{[L]}}{swc_{[i]}*Layer_{[i]} + FLUX_{[L]}} \quad (44)$$

$$UpN = sNO_3*\frac{FLOW_{[L]}}{swc_{[i]}*Layer_{[i]} + FLOW_{[L]}} \quad (45)$$

2.6. Calibration and validation of the updated CUPPA-Tea

The model was first calibrated using annual tea yields collected between 1989 and 1995 from a replicated irrigation and fertilizer experiment from the Ngwazi Tea Research Unit in Tanzania (8°33′S, 35°10′E, altitude 1840 m) (Fig. 5). The experiment comprised Clone 6/8 planted in the late 1960s on a sandy clay soil over clay (Stephens and Carr, 1991) with water-filled pore space at field capacity, ranging from 46 to 59%. The mean annual rainfall was 839–1121 mm with the majority falling between late November and May (Table 1; Annex B - Fig. B1). Field measurements showed that the tea rooted to a depth of 5 m. The soil organic carbon content was measured as 1.61% at 15 cm to 0.70% at 70 cm (Burgess and Sanga, 1993), and it was assumed that the organic carbon content was 0% at 500 cm. It was assumed that the pH ranged from 4.6 at 15 cm to 4.2 at 70 cm (Burgess and Sanga, 1993), and to 6.0 at 500 cm.

The six nitrogen treatments comprised annual applications 0, 150,

Table 1
Description of Ngwazi and Kericho trials, as used in CUPPA-Tea.

	Ngwazi Tea Estate, Tanzania	Kericho Tea Estate, Kenya
Irrigation treatments	I0, I1, I2, I3, I4, I5	Not applicable
Fertilizer treatments and N application (kg N ha^{-1})	N0: 0, N1: 150, N2: 225, N3: 300, N4: 375, N5: 450	N0: 0, N1: 90, N2: 180, N3: 270
Prune date	25 Nov 1990	1 Jun 2015 and 20 Feb 2019
N appl. Date	1-Jan 1-Jul	1-Jul
Soil texture	Sandy clay over clay	Medium sandy clay loam
Soil depth (cm)	500	300
Fertilizer type	Urea ammonium nitrate	Urea
Annual rainfall (mm; range across years)	839–1121	1341-3576
Soil organic carbon (depth in cm, % in italics)	15, *1.61*; 70, *0.7*; 500, *0*	10, *4.0*; 40, *3.5*; 80, 2.8; 120, *1.3*; 150, *1.3*; 300, *1.3*
Soil pH (depth in cm, pH in italics)	15, *4.6*; 70, 4.2; 160, *4.9*; 200, *5.8*; 260, *5.4*; 500, *6.0*	5, *4.01*; 15, *4.05*; 30, *4.05*; 45, *4.05*; 60, *4.05*, 90, *4.05*; 120, *4.05*; 150, *4.05*; 300, *4.05*
Water-filled pore space at field capacity (%)	46–59	59

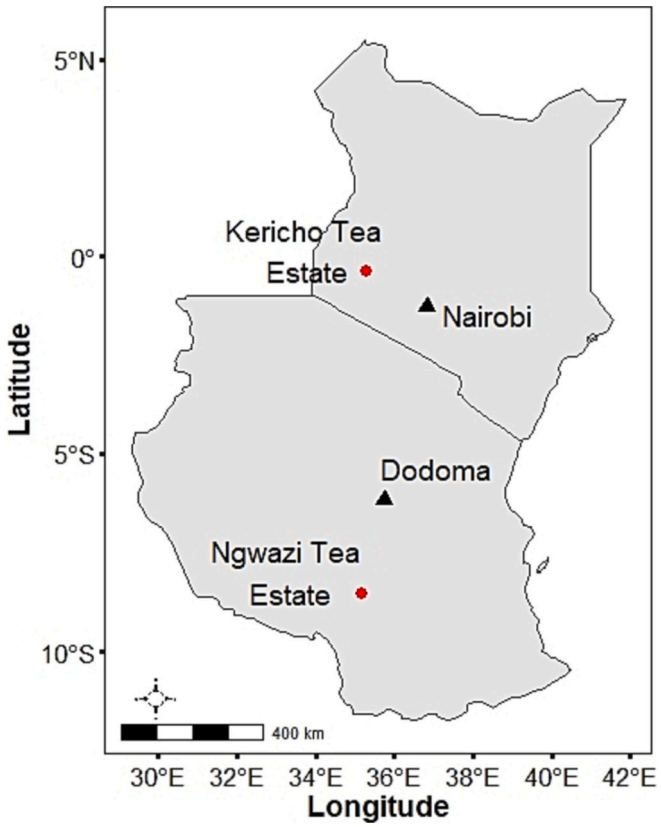


Fig. 5. Tea yield data for calibration were derived from Ngwazi Tea Estate in Tanzania and validation data from Kericho Tea Estate in Kenya.

225, 300, 375, or 450 kg N ha^{-1} with N, P_2O_5, and K_2O applied in a 2:1:1 ratio. There were also five irrigation treatments ranging from unirrigated tea (Treatment: I0) to tea receiving 50 mm of irrigation whenever the soil water deficit reached 50 mm (Treatment: I4). In the treatments receiving irrigation the fertilizer application was split equally between applications on 1 January and 1 July, whereas all the annual fertilizer application was applied on 1 January during the wet season in the treatment I0 receiving no irrigation. The primary form of nitrogen fertilizer applied was urea and ammonium nitrate. The tea was pruned on 25 November 1990.

The validation of the nitrogen algorithm was completed using annual tea yield data collected from an area of clone MRTM1 on the Kericho Tea Estate in Kenya (0°36′S, 35°28′E, altitude 2002 m) between 2015 and 2020 (Fig. 5). Mean annual precipitation ranged from 1341 to 3576 mm (Table 1; Annex B - Fig. B2). The soil was defined as medium sandy clay loam, with an assumed soil depth of 300 cm and a water-filled pore space at field capacity of 59% (Table 1). The soil organic carbon content was assumed to be 4.0% at 10 cm, declining to 1.3% at 300 cm. The pH was assumed to be about 4 throughout the soil profile. The fertilizer was applied once a year, (every 1 July) as urea at 0, 90, 180 or 270 kg N ha^{-1}. The tea was pruned on 1 June 2015 and 20 February 2019. Analytical model assumptions per site, on the crop management, initial conditions, clonal parameters and soil parameters are presented in Annex A.

For both the calibration and the validation dataset, statistical analysis was carried out using R (R Core Team, 2022). Linear regression was described using the R^2, root mean square error (RMSE), and modelling efficiency (EF). EF provides a comparison of the efficiency of the chosen model to the efficiency of describing the data as the mean of the observations (Smith et al., 1997). Values for EF can be positive or negative with a maximum value of 1. A positive value indicates that the simulated values describe the trend in the measured data better than the mean of the observations. Smaller and negative values indicate that the simulated values describe the data less well compared to the mean of the observations.

3. Results

3.1. Model calibration and validation

Including the nitrogen algorithm allowed the CUPPA-Tea model to predict annual yields across the six nitrogen treatments x five irrigation treatments x seven years (210 datum points) that explained 79% of the variation in the observed yields at Ngwazi in Tanzania (Fig. 6). The measured tea yields ranged from 542 to 6291 kg ha^{-1}. The slope of the best fit linear regression was 0.84, the RMSE error was 660 kg ha^{-1}, and the modelling efficiency (EF) was 0.77.

The same R^2 value of 79% was obtained when the predicted yields for the four nitrogen treatments x six years (24 datum points) for the Kericho experiment were compared to measured values (Fig. 6). The measured yields ranged from 1440 to 5412 kg ha^{-1}. The slope of the best fit linear regression was 0.72, the RMSE error 507 kg ha^{-1}, and a similar modelling efficiency (EF) of 0.75. At each site, the lowest yields occurred in the year post prune (1991 in Tanzania and in 2016 in Kenya).

3.2. System nitrogen balance

The CUPPA-Tea model was used to derive an initial nitrogen stock and then annual flows of nitrogen between organic and inorganic forms in the soil and nitrogen held by the plant for both sites (Table 2 and Table 3). In the Kenyan experiment in 2015, most of the nitrogen in the tea agroecosystem was held in the form of soil organic N (46,672 kg N ha^{-1}), primarily as humus (46,157 kg N ha^{-1}) (Table 2). The next largest stock was N stored within the crop (1565 kg N ha^{-1}), and the initial amount of mineral N was assumed to be minimal (1 kg N ha^{-1}), as the model assumed the rapid uptake of mineral N. Within the treatment receiving 270 kg N ha^{-1} of fertilizer, an annual addition of 270 kg N ha^{-1} was assumed in the model. The quantity of N removed as harvested leaf was assumed to range from 90 kg N ha^{-1} in 2015 (when the tea was pruned on 1 June) to 212 kg N ha^{-1} in 2020 (following pruning in February 2019). Volatilisation losses were almost zero, whereas N_2O losses through denitrification and nitrification were zero due to the assumed low pH of <4.1 (Table 1). Leaching losses were also effectively zero due to the assumption that any N released from urea hydrolysis was added to the soil ammonium pool, which was considered immobile in soil profile (Annex A-Table A7).

Although the losses from the system were minimal, the model predicted changes between the nitrogen stored in the plant, and as soil organic and inorganic nitrogen. The N level stored in the plant was predicted to increase from 1567 kg N ha^{-1} in early January 2016 to 2488 kg N ha^{-1} in January 2019, prior to pruning in February 2019. The level of inorganic nitrogen was predicted to be low (typically 1 kg N ha^{-1}) except in January 2020 following pruning in the preceding year. In Kenya, all of the N applied to the experiment was added in July. The level of fresh organic nitrogen was higher in January 2016 than January 2015, following pruning in June 2015, and higher in January 2020 than January 2019 following pruning in February 2019. The level of soil organic nitrogen stored as humus was relatively stable.

Completing a similar analysis for tea receiving 300 kg N ha^{-1}, under rainfed conditions in Tanzania, suggested lower levels of soil organic nitrogen (about 13,500 kg N ha^{-1}) than in Kenya (46,000 kg N ha^{-1}), directly related to the assumed lower level of soil organic carbon (0–1.6% compared to 1.3–4.0%). The level of plant nitrogen in Tanzania (1800–2527 kg N ha^{-1}) was broadly similar to that in Kenya (1565–2488 kg N ha^{-1}). However, the level of inorganic nitrogen on 1 January was substantially higher (182–195 kg N ha^{-1}), than in Kenya, because it was assumed that in the unirrigated treatment all of the nitrogen fertilizer was applied on 1 January. In Tanzania the tea was

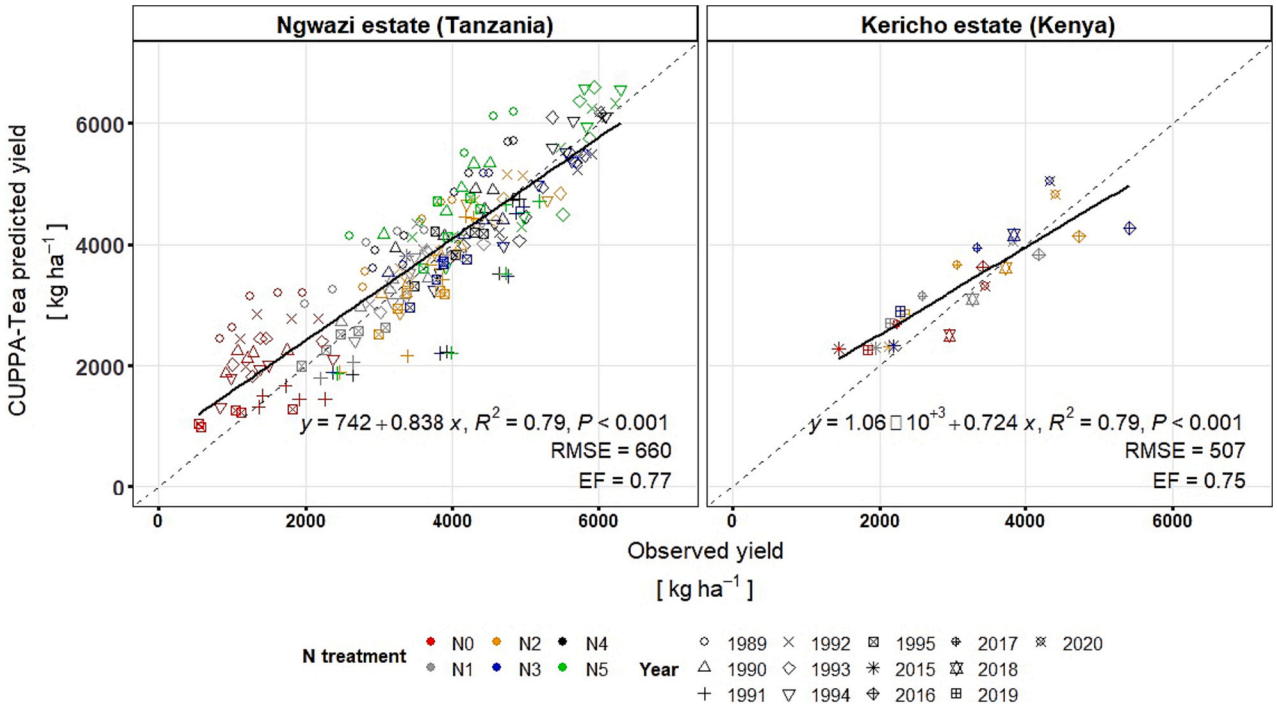


Fig. 6. Linear regression analysis of the predicted yields using the CUPPA-Tea model with observed yields from a) Ngwazi Estate in Tanzania (1989–1995) and b) Kericho Estate in Kenya (2015–2020) experiments (Dashed line: 1:1; RMSE: root mean square error; EF: Modelling efficiency; shapes indicate year and colors N treatment).

pruned in November 1990, and a significant leaching loss of 92.4 kg N ha^{-1} was predicted in 1991. Because the pH in Tanzania was assumed to be 4.2–6.0, compared to about 4.0 through the whole profile in Kenya, the nitrification of ammonium to nitrate was possible (Table 3).

3.3. N response curves and sensitivity to soil organic carbon

Within the modified CUPPA-Tea model, it was possible to predict the impact of soil organic carbon (SOC) content on the response of tea yields to N applications. To investigate this, a sensitivity analysis for different initial SOC values per tea estate was conducted. Fig. 7 presents how the default N response would change when the initial SOC: i) is null, ii) 1.6%, iii) 4% and iv) 8%. Soil depth was 500 cm and 300 cm, whilst the default SOC content at the top 15 cm was 1.6% and 4.0% for Ngwazi and Kericho respectively (Annex A-Table A5).

In general, the modelled yield at 1.6% SOC (the default value in Tanzania) matched the measured yield in Tanzania (Fig. 7a and b), and the modelled yield at 4% SOC (the default value in Kenya) matched the yield measured in Kenya (Fig. 7c). At both sites, CUPPA-Tea predicted that higher SOC contents resulted in higher mean tea yields, with the effect being greatest when no fertilizer was applied (Fig. 7). Under rainfed conditions and no fertilizer application, the mean modelled yield at Kericho at a SOC of 4% (3033 kg ha^{-1}) was marginally higher than at Ngwazi (2318 kg ha^{-1}), possibly as a result of the higher rainfall levels in Kenya. Under rainfed conditions with no fertilizer, the predicted effect of increasing the SOC from 0% (red line) to 8% (orange line) was 1783 kg ha^{-1} in Tanzania and 2180 kg ha^{-1} in Kenya. Under irrigated conditions with no fertilizer, increasing the SOC from 0% to 8% in Tanzania, resulted in a predicted yield benefit of about 4000 kg ha^{-1}. At high levels of nitrogen application, the effect of SOC was reduced, with a minimal yield response to changes in SOC for rainfed tea in Tanzania at an application rate of 450 kg N ha^{-1} (Fig. 7).

4. Discussion

The results are discussed in terms of the importance of including N dynamics in crop models, the significance of developing N response tools, understanding N environmental losses, organic tea production and limitations and future research.

4.1. Including N in crop models

Nitrogen (N) especially inorganic N is typically the most limiting nutrient for tea growth and development (LeBauer and Treseder, 2008). Considering that crop modelling originated approximately five decades ago (Hoogenboom et al., 2020), crop models that account for nitrogen dynamics are still relatively rare although some exist (e.g. Jones et al., 2003; Wolf, 2012; Holzworth et al., 2014). Such crop models that adequately describe daily interactions of the soil-plant-atmosphere interface can help managers understand the functioning of the farming system and assist them in decision making. In this paper, we have demonstrated that it is possible to successfully develop a working model of N responses in tea that have been calibrated for an experiment in Tanzania and validated for an experiment in Kenya. The calibrated and validated models were able to explain 78–79% of the variation in tea yields across different years, different fertilizer and drought treatments and different stages of prune. Across the two sites, the slope of the best fit regression line was 0.72–0.84, which suggests that there was a tendency to overestimate yields in years of prune, and to underestimate the highest yields. This moderating effect of models so that they tend to not predict the full range of field observations seems to be a common feature of a range of models (Giannitsopoulos et al., 2021; Beka et al., 2022). The integration of N responses in CUPPA-Tea allows investigation of interactions between fertilizer application rates, climate, drought, and soil type. By including N responses, the model improved its estimates compared to simulations where for instance the nitrogen routine was turned off (Table 4; Annex A-Fig. A3).

The interaction between water availability and nitrogen is demonstrated in Table 5. The model predicted, for a constant SOC, that yield responses to nitrogen application were greater under non-limiting water conditions. A reason for this is that water is necessary to enable the uptake of soil N by the crop, and well-watered conditions can also

Table 2
The calculated stock of N stored within the crop and the soil (as organic or inorganic N) and the annual flows of N between those stock between 2015 and 2020, for Kericho treatments receiving an annual fertilizer of 270 kg N ha^{-1}.

	2015	2016	2017	2018	2019	2020
Beginning of year (kg N ha^{-1})						
Plant N	1565	1567	1866	2178	2488	2043
Soil inorganic N	1	1	3	1	1	363
Soil organic N (Humus N)	46,157	46,034	45,898	45,777	45,624	45,515
Soil fresh org. N (Litter + dead roots)	515	815	759	695	657	959
Total N	48,238	48,417	48,526	48,651	48,770	48,880
Additions to system (kg N ha^{-1} yr^{-1})						
Mineral N fertilizer	270	270	270	270	270	270
Atm. deposition of N	0	0	0	0	0	0
Removals from system (kg N ha^{-1} yr^{-1})						
Harvest of tea	90	161	145	150	160	212
Leaching loss	0	0	0	0	0	0
Volatilisation loss	0.042	0.006	0.014	0.007	0.08	0.09
N_2O loss (Denitrification)	0	0	0	0	0	0
N_2O loss (Nitrification)	0	0	0	0	0	0
Total losses	90	161	145	150	160	212
Transfer within system (kg N ha^{-1} yr^{-1})						
Plant N to soil organic N	436	66	0	0	298	459
Soil organic N to soil mineral N	259	259	184	191	106	161
Soil mineral N to plant N	529	527	457	461	13	794
Change in stock (kg N ha^{-1} yr^{-1})						
Change in inorganic N	0	2	-2	0	362	
Change in tea plant N	2	299	312	310	−445	
Change in organic N	177	−192	−185	−191	193	

enhance soil mineralization and high levels of microbial activity (Schimel et al., 2007; Plaza-Bonilla et al., 2022) (Table 5).

In Tanzania for example, the high irrigation treatment, as expected, resulted in greater yields than the rainfed tea across all N applications. It is worth noting that at 0% SOC (Fig. 7a and b; red line) and under high N application, fertilizer was better utilized under fully irrigated (I4) than under rainfed (I0) conditions, with predicted yields being 5442 kg ha^{-1} and 3964 kg ha^{-1} respectively. On average, the amount of N taken up by the tea plants under fully irrigated conditions was predicted to be about 10% higher than that under rainfed conditions (Table 5).

The transport of mobile ions in the soil depends on the soil water content both in terms of enabling simple diffusion and transpiration-driven mass flow (Plett et al., 2020). This was also apparent at both sites under rainfed conditions where the higher potential soil water deficit in Tanzania (mean of 818 mm) than in Kenya (mean of 425 mm) was associated with reduced gross N uptake by the crop of 340 kg N ha^{-1} compared to 464 kg N ha^{-1} at the Kenyan site (Table 5). However, it is worth noting that if soil water contents remain permanently high, oxygen deprivation can affect the functioning of aerobic microorganisms thereby decreasing the conversion of organic to inorganic nitrogen (Moyano et al., 2012).

4.2. Developing financial N response tools

There are a range of methods for estimating the optimum level of fertilizer application. Generally, agronomists advocate for the implementation of "4R" practices to optimise nitrogen use, which involves applying fertilizer at the right rate, right time, right source and right placement in the soil (Sposari and Flis, 2017). At a minimum, a decision may be taken to simply replace the nitrogen removed in the harvested leaf. In Kenya, at a nitrogen application rate of 270 kg N ha^{-1}, in unpruned years between 145 and 212 kg N ha^{-1} were removed as harvested shoots, equivalent to 53% and 79% of applied N. Ensuring that such a level of nitrogen application is made, ensures that the total amount of nitrogen in the system does not decline.

An alternative method is to determine the response curve of yield to nitrogen fertilizer, account for any effect of nitrogen on tea quality, and include assumptions regarding the price of nitrogen fertilizer and the value of harvested tea. Using the modelled response curves for pruned and unpruned tea in Kenya, it is possible to establish marginal revenue

Table 3
The stock of N stored within the crop and the soil (as organic or inorganic N) and the annual flows of N between those stock between 1989 and 1995, for Ngwazi treatments receiving an annual fertilizer of 300 kg N ha^{-1} under rainfed conditions.

	1989	1990	1991	1992	1993	1994	1995
Beginning of year (kg N ha^{-1})							
Plant N	1800	1948	1964	1992	2101	2245	2527
Soil inorganic N	188	187	186	195	182	190	188
Soil organic N (Humus N)	13,625	13,572	13,515	13,462	13,413	13,366	13,323
Soil fresh org. N (Litter + dead roots)	136	121	320	435	607	585	566
Total N	15,749	15,828	15,985	16,084	16,303	16,386	16,604
Additions to system (kg N ha^{-1} yr^{-1})							
Mineral N fertilizer	300	300	300	300	300	300	300
Atm. deposition of N	0	0	0	0	0	0	0
Removals from system (kg N ha^{-1} yr^{-1})							
Harvest of tea	126	120	94	144	137	114	102
Leaching loss	0	0	92.4	3.8	0	0	0
Volatilisation loss	1.12	1.11	1.23	1.13	1.11	1.13	1.12
N_2O loss (Denitrification)	0	0	0.02	0.01	0	0.01	0
N_2O loss (Nitrification)	0.03	0.07	1.24	0.21	0.02	0.28	0.24
Total losses	127	121	189	149	138	115	103
Transfer within system (kg N ha^{-1} yr^{-1})							
Plant N to soil organic N	0	207	70	193	0	0	0
Soil organic N to soil mineral N	68	67	9	69	69	62	70
Soil mineral N to plant N	369	363	178	376	370	358	367
Change in stock (kg N ha^{-1} yr^{-1})							
Change in inorganic N	-1	-1	10	−14	8	−2	
Change in tea plant N	148	16	28	109	144	282	
Change in organic N	−68	142	62	123	−69	−62	

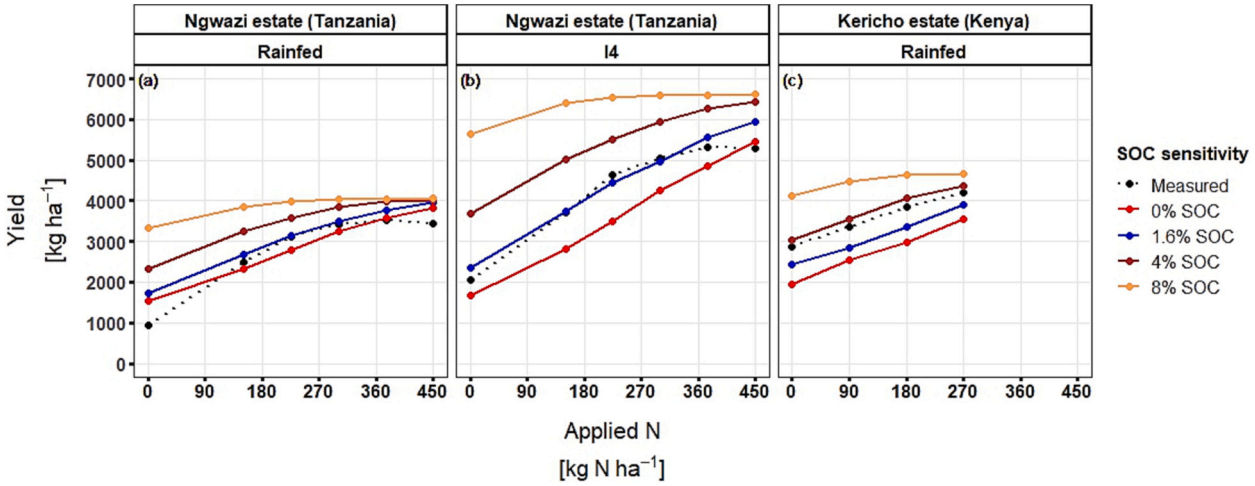


Fig. 7. Predicted effect of soil organic carbon (SOC) content (0, 1.6, 4 and 8%) on the tea yield response to nitrogen application in unpruned years (mean yields of unpruned years) for a) rainfed tea and b) fully irrigated tea in Tanzania (I4), and c) rainfed tea in Kenya. Default SOC values for Ngwazi and Kericho were 1.6% and 4% respectively.

Table 4
Comparison of CUPPA-Tea goodness of fit for Ngwazi and Kericho when the N algorithms turned on and off.

	Ngwazi		Kericho	
	N: On	N: Off	N: On	N: Off
R^2	0.79	0.12	0.79	0.62
RMSE	660	2238	507	1194
EF	0.77	−1.63	0.75	−0.38

and costs curves for unpruned and pruned tea. The assumptions included a value of fertilizer cost of 1.00 US$ per kg of urea, and 0.41 US$ per kg of green harvested leaf, with a dry matter content of 0.22 and a transport cost to the factory of 0.005 US$ per kg of green harvested leaf (assuming a distance to the factory of 10 km; Annex A-Table A6). The results suggest that, based on these assumptions, tea profitability is maximized by applying 300 kg N ha^{-1} to unpruned tea and about 70–150 kg N ha^{-1} to pruned tea (Fig. 8). The above assumptions reflect the cost of fertilizer in early 2023, which is substantially higher than the value in 2019 (0.20 US$ per kg of urea; Index Mundi, 2022).

Across the world, nitrogen fertilizer is commonly applied to tea, and in Zhejiang Province in China, mean annual application rates have been as high as 520 kg N ha^{-1}, even though this is 2 to 2.5 times higher than the recommended rate (Ma et al., 2013). In fact, there are cases such as in Japanese tea, where N application can reach 1200 kg N ha^{-1} yr^{-1} (Nakasone, 2009).

4.3. Environmental consequences of nitrogen losses

In addition to financial consequences, losses of N can have negative environmental implications (Rebello et al., 2022). Hence the optimal application of N may also depend on the societal cost of N lost to the environment. Ideally, nitrogen fertilizer should be applied in a way that it is available to the tea plant, without being lost to aqueous or atmospheric environments where it can be a major pollutant (Farzadfar et al., 2021).

When and where N will be lost can be dependent on the rainfall intensity, soil cover, and the soil's physical condition (Vagstad et al., 1997; Patil et al., 2010). N losses in soil systems can include nitrate and ammonium leaching, ammonia volatilisation and denitrification (emission of N_2O) (Musyoka et al., 2019; Zou et al., 2021). Within the model, surface runoff losses of nitrogen were not considered as the experimental sites were on relatively level ground. In practice, as tea is often grown on steep slopes, the assumption of no runoff losses may be incorrect.

Leaching: within the CUPPA-Tea model, the predicted rates of nitrate leaching are typically small because of i) the low levels of inorganic

Table 5
Estimated maximum potential soil water deficit (PSWD), nitrogen mineralization rate ($N_{mineralise}$) (kg N ha^{-1}) and nitogen uptake (N_{uptake}) in Ngwazi, Tanzania (300 kg N ha^{-1} applied under rainfed (I0) and high irrigation treatment (I4)) and in Kericho, Kenya (270 kg N ha^{-1} applied under rainfed conditions) for each of six or seven years.

Treatment	Parameter[a]	Units	1989	1990	1991[b]	1992	1993	1994	1995	Mean
Tanzania										
Rainfed	PSWD	(mm)	739	723	854	758	893	914	842	818
	$N_{mineralise}$	(kg N ha^{-1} yr^{-1})	68	67	8.5	69	69	62	70	59
	N_{uptake}[c]	(kg N ha^{-1} yr^{-1})	369	363	178	376	370	358	367	340
Irrigated	PSWD	(mm)	89	89	110	79	95	74	233	110
	$N_{mineralise}$	(kg N ha^{-1} yr^{-1})	98	95	61	98	94	90	90	89
	N_{uptake}[c]	(kg N ha^{-1} yr^{-1})	399	386	255	399	394	389	391	373
Kenya										
Treatment	Parameter			2015[b]	2016	2017	2018	2019[b]	2020	
Rainfed	PSWD	(mm)		504	300	427	324	710	286	425
	$N_{mineralise}$	(kg N ha^{-1} yr^{-1})		259	259	184	191	106	161	193
	N_{uptake}[c]	(kg N ha^{-1} yr^{-1})		529	527	457	461	13	794	464

[a] Potential soil water deficit (PSWD) as the maximum value per year and site calculated as the sum of potential evapotranspiration minus amount of rainfall and irrigation (if any).
[b] The tea was pruned on 25 November 1990 in Tanzania and 1 June 2015 and 20 February 2019 in Kenya.
[c] The N_{uptake} is a gross uptake, N is also returned to the soil through litter fall and root turnover.

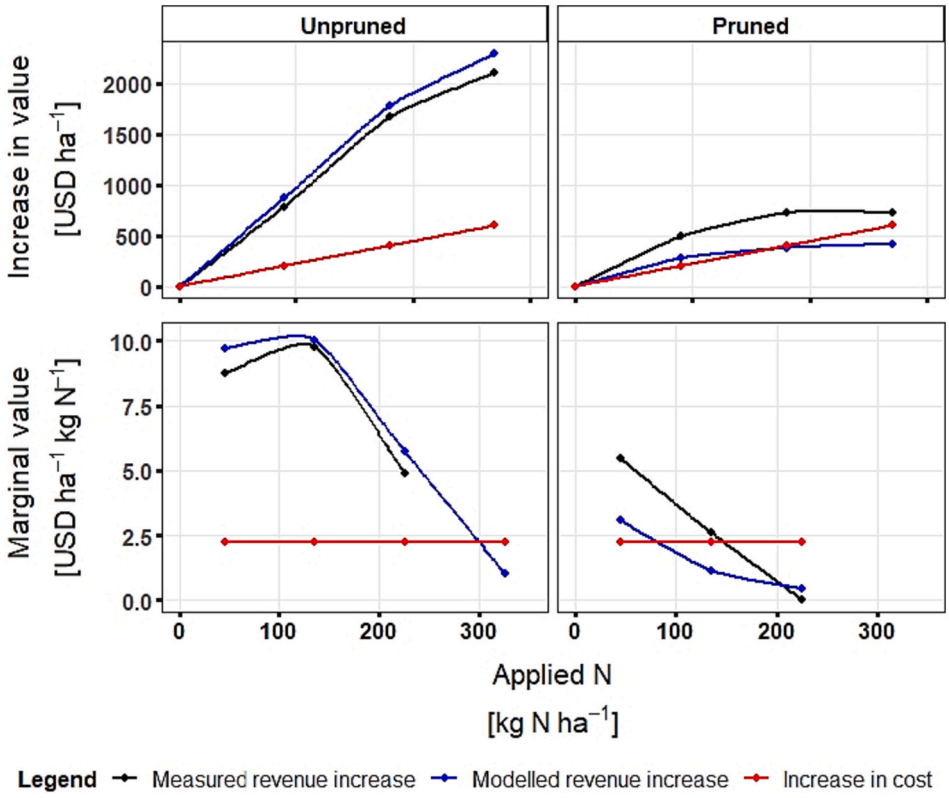


Fig. 8. Predicted revenue and costs of applying different levels of nitrogen fertilizer in Kericho, based on measured and modelled yields in unpruned and pruned tea in Kenya (assumed 108 KSh = 1 USD) assuming a soil organic carbon (SOC) content of 4%.

nitrogen in the soil, ii) the acidic soils which prevent nitrification, and iii) the relatively deep tea roots (3–5 m). At Kericho, under the default pH of 4.0, average N losses across all N applications and years were zero (Table 6). The algorithms used in the CUPPA-Tea model assumed that soil nitrification was zero at pHs less or equal to 4.5 and greater or equal to 9.0.

At a slightly higher pH of 4.51, the model predicted an annual leaching rate of 1 to 18 kg N ha^{-1} yr^{-1} in years when the tea was not pruned (Table 6). The reason for the relatively low values, is that the algorithms calculate that N applied as urea (as in Kenya) is rapidly hydrolysed and converted to ammonium, which in turn is assumed to not be transported through the soil profile. At low pHs, the nitrification rate is also low which in turn means lower NO_3^- concentration and consequently lower N movement through leaching (Table 6). In Taihu China, Zhou et al. (2022) reported N leaching losses of 73, 200 and 240 kg N ha^{-1} in a dry, normal and wet year respectively, when 209 and 174 kg N ha^{-1} urea was applied in March and October respectively. In that study mean annual air temperature and precipitation over 60 years were 15.9 °C and 1157 mm respectively, tea was older than 15 years, soil texture was silt loam, and mean pH was as high as 6.15. We would argue that the high pH is a major determinant of the high leaching losses. If we assume a higher pH for the soil in Kenya of 4.51, then the model does predict that a leaching loss of 143 kg N ha^{-1} yr^{-1} could be possible if 270 kg N ha^{-1} is applied in a year of prune (e.g., 2019) (when crop N uptake is reduced and additional N can be provided in the soil by the release of N from pruning and the turnover of roots) (Table 6).

Volatilisation: Within this study, the predicted volatilisation losses in Kenya at a pH of about 4 were minimal (Table 6) and remained minimal

Table 6
Effect of pH values of 4.04, 4.51, and 5.00 on the predicted annual level of leaching (N_{leach}), nitrification ($N_{nitrify}$), denitrification ($N_{denitrify}$) and volatilisation ($N_{volatilise}$) at the Kericho site from 2015 to 2020, assuming an application rate of 270 kg N ha^{-1} across the soil profile.

Flux	pH	Predicted N flux (kg N ha^{-1} yr^{-1})						
		2015	2016	2017	2018	2019	2020	Mean
$N_{nitrify}$	4.04	0	0	0	0	0	0	0
$N_{nitrifyN2O}$	4.04	0	0	0	0	0	0	0
$N_{denitify}$	4.04	0	0	0	0	0	0	0
N_{leach}	4.04	0.05	0	0	0	0	0	0.01
$N_{volatise}$	4.04	0.04	0	0.01	0	0.08	0.09	0.04
$N_{nitrify}$	4.51	125	11	9	7	204	107	77
$N_{nitrifyN2O}$	4.51	1.17	0.07	0.01	0.03	1.85	0.84	0.66
$N_{denitify}$	4.51	0	0	0	0	0	0	0
N_{leach}	4.51	2.9	1	3	1	143	18	28
$N_{volatise}$	4.51	0.10	0.04	0.05	0.04	0.16	0.12	0.09
$N_{nitrify}$	5.00	275	46	34	18	362	65	133
$N_{nitrifyN2O}$	5.00	2.57	0.35	0.15	0.06	3.5	0.60	1.21
$N_{denitify}$	5.00	0.04	0	0	0	0.14	0	0.03
N_{leach}	5.00	9	2	10	3.6	289	16	55
$N_{volatise}$	5.00	0.21	0.13	0.13	0.12	0.23	0.15	0.16

(0.16 kg N ha^{-1} yr^{-1}) at a pH of 5. The use of the model with an assumed pH of 7.0 would lead to a predicted mean annual volatilisation rate across years of 16 kg N ha^{-1} yr^{-1} (data not shown). Field studies on tea volatilisation losses are relatively scarce. In a glasshouse experiment, Liyanage et al. (2015) showed that mean percentages of ammonia volatilized, in Sri Lanka, can reach 27% of applied N as urea, for pH values of 4.46–4.84, and soil bulk densities of 1.48–1.53 g cm^{-3}. In the temperate conditions of the United Kingdom, Bishop and Manning (2010) reported mean N losses to the environment through volatilisation of NH_3 of around 19% of applied N (mean application rate: 130 kg N ha^{-1}) and 17% of applied N (mean application rate: 100 kg N ha^{-1}) from grassland and arable soil respectively.

N_2O losses: denitrification and nitrification rates were also low in this study, driven in part by the low soil pH values and the generally well-aerated soil conditions (Annex A-Fig. A2). Annual denitrification rates in Zhou et al. (2022) for a tea garden in China ranged from 1.76 to 2.30 kg N ha^{-1}. Our mean calculated rates of N_2O emissions from nitrification ranged from 0 to 1.21 kg N ha^{-1} yr^{-1} at a pH of 4.0 to 5.0, and assuming an application of 270 kg N ha^{-1} (Table 6). Higher N_2O emissions have been reported at higher application rates including 10.6 kg N ha^{-1} yr^{-1} from the application of 510 kg N ha^{-1} yr^{-1} on tea in Japan with a soil pH of 3.4 (Hirono and Nonaka, 2012). Emissions of N_2O of 7.1 and 17.2 kg N ha^{-1} yr^{-1} have been observed in Hunan, China for non-fertilised and conventional (410 kg N ha^{-1} yr^{-1} applied) treatments respectively (Fu et al., 2012) at soil pH of 4.5. The reported global mean value of fertilizer N-induced direct emission factor of N_2O from global tea plantations is 2.31%, which is two times higher than the IPCC default value of 1% (Hergoualc'h et al., 2019; Wang et al., 2020).

4.4. Organic tea

The updated CUPPA-Tea model could be useful in supporting decisions regarding the management of organic tea, i.e., tea not receiving mineral N applications. The nitrogen model algorithms can be used to predict the N derived from the breakdown of fresh and recalcitrant organic matter (humus), and the use of the model alongside experimental calibration and validation could provide useful insights into the effect of the addition of organic fertilizers. One potential effect of the addition of organic fertilizers is to raise the soil pH (Yan et al., 2018), and reduce the level of soil acidification in tea plantations (Xie et al., 2021). This increase in soil pH could increase leaching and volatilisation losses (Benbi and Nieder, 2003). The application of organic matter (e.g. residues) with a high C:N ratio can also temporarily lock N within soil microorganisms (immobilisation). However, this N source can again be available for uptake by the crop when microorganisms die. In a 41-year experiment in Germany, soil carbon stocks in various crops such as rye, wheat, maize and barley, appeared to be higher when organic inputs were combined with mineral fertilizer, compared to only organic inputs or only mineral fertilizer (Hijbeek et al., 2017). In addition, Bagchi et al. (2020) reported that organically grown tea can also have higher polyphenol content than tea grown with mineral fertilizers.

The results in Fig. 7, demonstrate that the yield losses due to removal of inorganic nitrogen application can be partly offset by ensuring that the soil organic carbon content is high. By contrast in a global meta-analysis focused on experimental results with maize, Oldfield et al. (2019) reported that steeper nitrogen response curves can be achieved with higher levels of SOC. One possible reason for this contrasting result is that increased soil organic carbon contents may provide additional benefits than just the supply of nitrogen, which has been the focus of this study. For example, high levels of organic matter content can also improve soil structure, increase water holding capacity, soil biodiversity, and reduce soil erosion risk (Johnston, 1986; Lal, 2009).

4.5. Limitations and future research

The outputs of any computer simulation model are limited by the assumptions made (Table A7). The CUPPA-Tea model assumes fertilizer is uniformly incorporated into the topsoil layer and that there are no effects of pest and diseases. In addition, no P or K deficiency is assumed, and the model does not deal with ammonium transport within the soil profile. One additional change in a future iteration of the model would be to include a dynamic pH response where the pH could alter depending on the forms of fertilizer used, as well as calculations of N loss from surface water (runoff). Even though 2.2 to 10.3 kg N ha^{-1} yr^{-1} of reported N deposition may seem minimal, it still raises e.g. a 100 kg N ha^{-1} application by 10%. Thus, N deposition may be included in future versions of CUPPA-Tea. Although an initial attempt has been made to include algorithms to apply residue or manure as fertilizer source in CUPPA-Tea, these have not been tested yet. Finally, for an integrated "whole system" approach, future CUPPA-Tea versions would benefit from algorithms that estimate the social cost of nitrogen, following for instance approaches similar to Keeler et al. (2016).

5. Conclusions

Sustained production of high tea yields depends on the steady supply of nitrogen from the soil to meet plant requirements. For field use of the CUPPA-Tea model, we found that the yield responses to applied N were particularly sensitive to changes in the soil organic carbon content, availability of soil water, and pH. The inclusion of N algorithms in the model gave accurate predictions of annual tea yields in two experiments, and CUPPA-Tea estimated low N losses to the environment provided pH levels were at about 4.0. The model highlighted in the absence of mineral N applications, higher tea yields were obtained on sites with a high rather than a low soil organic carbon content. The benefits of a high soil organic carbon content on yield were less apparent at higher rates of mineral N application. Hence tea grown on soils with a low soil organic carbon contents tended to show a greater yield response than tea grown on soils with a high soil organic content. CUPPA-Tea also indicated the significance of water-limited conditions in reducing crop N uptake and in turn tea yields. Using such models as CUPPA-Tea can also aid in estimating the financial optimum N requirements and produce marginal revenue and cost curves after accounting for the analogous assumptions. Modelling different scenarios and testing various hypotheses can help the user make the right decisions with regards to sustainable tea production, aiming at profitable yields but at the same time protecting the natural environment.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Paul Burgess, Ann Holden and Ruben Sakrabani reports financial support was provided by Ekaterra UK Limited. All authors reports equipment, drugs, or supplies was provided by Ekaterra Tea Kenya Plc. Michail Giannitsopoulos, Paul Burgess, Ruben Sakrabani, Ann Holden, Helen Saini has patent #EP22386097.4 pending to Michail Giannitsopoulos, Paul Burgess, Ruben Sakrabani, Ann Holden, Helen Saini.

Data availability

Data will be made available on request.

Acknowledgments

We acknowledge support of the UKRI-Innovate UK research project "Data-led Soil Management for Low Income Farmers" Contract No 47864. We are also thankful to Unilever, ekaterra Research and Development UK Limited and ekaterra Tea Kenya PLC for their support and data provision throughout this project. We are also thankful for the constructive feedback from anonymous reviewers that has improved the paper.

Appendix A

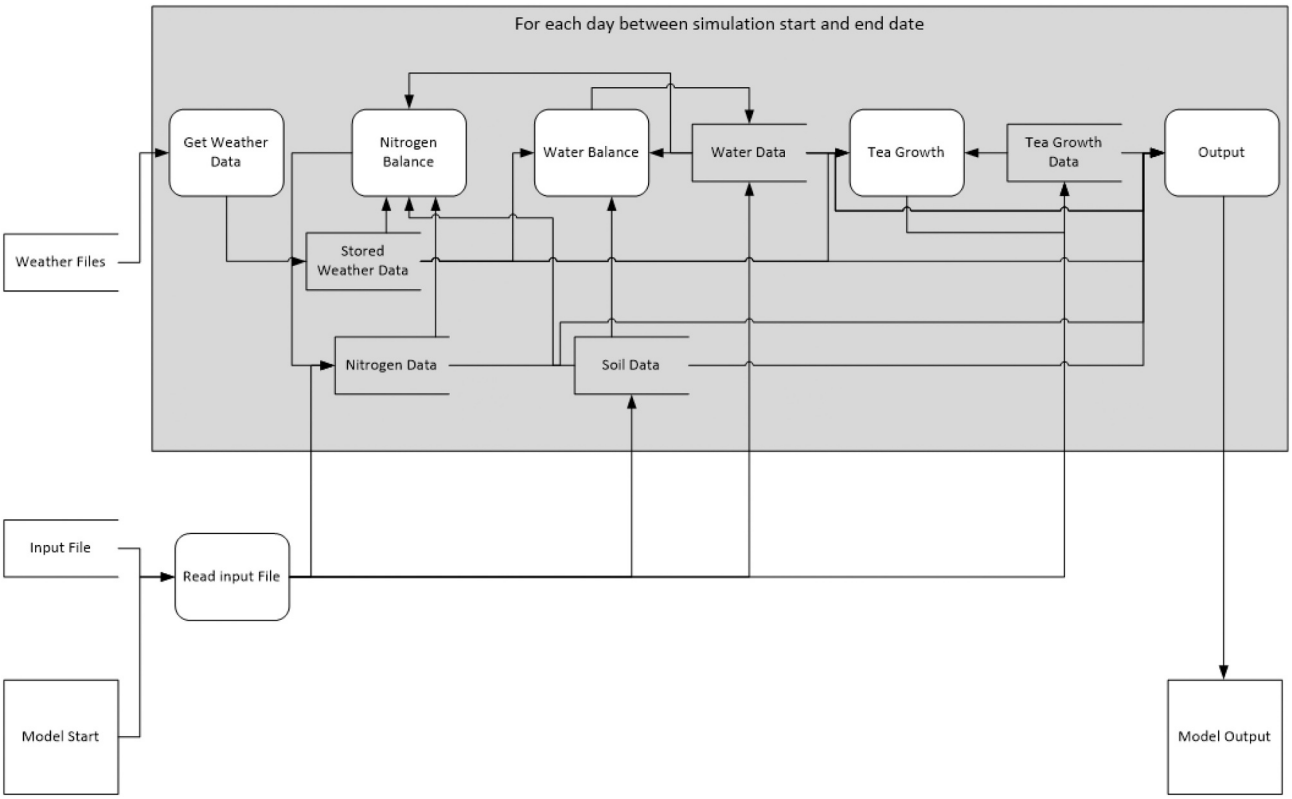


Fig. A1. Top-level diagram showing overview of CUPPA-Tea model.

Table A1. Crop management parameters assumptions in CUPPA-Tea.

Crop Management	Value		Units
	Tanzania	Kericho	
Population density	0.9259	0.9259	Bushes m^{-2}
Row spacing	1.2	1.2	m
Pluck upper limit	4	3	m
Pluck lower limit	2	2	m
Shear height	2	3	m
Pluck to leaf	1	1	–
Min pluck length	0	0	cm
Max pluck length	100	100	cm
Irrigation threshold	190	–	mm

Table A2. Initial conditions assumptions in CUPPA-Tea.

Initial conditions	Value		Units
	Tanzania	Kericho	
Fine root weight	190	190	g m^{-2}
Tops Residue	1000	1000	g m^{-2}
Leaf area index	6.5	6.5	m^2 m^{-2}
Root depth	550	300	cm
Tops residue fraction	0.01	0.01	–
Shoot No	1400	960	m^{-2}
Stem wood weight	2325.4	2325.4	g m^{-2}
Reserves weight	0	0	g m^{-2}
Green stem weight	200	200	g m^{-2}
Thick root weight	1245	1245	g m^{-2}
Table height	80	75	cm
TopsNFraction	0.0325	0.0325	–
Leaf weight	525.4	525.4	g m^{-2}
Root residue (dead roots)	200	200	g m^{-2}
Root N fraction	0.01	0.01	–
Prune base height	65	60	cm

Table A3. Initial root density, soil water, NH_4^+ and NO_3^- in CUPPA-Tea.

Initial conditions	Tanzania	Kericho	Units
Root density (cm depth, value)	25,3.4073,40,2.8067,55,2.312, 70,1.9045,90,1.4706,110,1.1355,130, 0.8768,150,0.6771,170,0.5228,190,0.4037, 210,0.3117,230,0.2407,250,0.1859,270,0.1435, 290,0.1108,310,0.0856,330,0.0661,350,0.051, 370,0.0394,390,0.0304,410,0.0235,430,0.0181,450, 0.014,470,0.0108, 490,0.0084,510,0.0064	Likewise	cm cm^{-3}
Soil water (cm depth, value)	25,0.266,40,0.287,55,0.297,70,0.288,90,0.271,110,0.274,130, 0.276,150,0.286,170,0.291,190,0.308,210,0.331,230,0.332,250, 0.340,270,0.347,290,0.331,310,0.338,330,0.321,350,0.318,370, 0.314,390,0.312,410,0.308,430,0.305,450,0.302,470,0.298,490,0.296	0.32	mm^3 mm^{-3}
NH_4^+ (cm depth, concentration)	15,25,50,26,200,0.6320,0,500,0	10,85,40,56,80,64,120,0,150,0,300,0	mg kg^{-1}
NO_3^- (cm depth, concentration)	15,56,50,74,200,1.5320,0,500,0	10,5,40,4,80,4120,0,150,0,300,0	mg kg^{-1}

Table A4. Clonal parameters assumptions in CUPPA-Tea.

Clonal parameters	Tanzania	Kericho	Units
Genotype name	6/8	MRTM1	–
Dry matter temperature response (temp, temp factor)	0,0,10,0,20,1,35,1,42,0	0,0,10,0,20,1,35,1,42,0	
Critical lower day length	11.25	11.25	h
Development optimum temperature	24	24	°C
Development maximum temperature	40	40	°C
Development base temperature	8	8	°C
Critical saturation deficit	2.3	2.3	kPa
Saturation deficit sensitivity	0.43	0.43	kPa^{-1}
Critical delta daylength	−0.001	−0.001	
Critical shoot day length	12	12	h
Extension base temperature	10	10	°C
Critical upper daylength	12.15	12.15	h
Stage2 development rate	0.212	0.212	$(Dd)^{-1}$
Stage2 extension rate	0.537	0.537	mm Eu^{-1}
Stage1 development rate	0.0381	0.0381	$(Dd)^{-1}$
Stage1 extension rate	0.0129	0.0129	mm Eu^{-1}
Root depth growth rate	0.2	0.055	cm d^{-1}

(*continued on next page*)

(*continued*)

Clonal parameters	Tanzania	Kericho	Units
Mean last leaf	5.3	5.3	#leaves
Extinction coefficient	0.7	0.7	–
Shoot day length sensitivity	0.4	0.4	h^{-1}
Shoot coefficient of variation	0.3	0.3	–
Weight stage slope	0.055	0.055	g $leaf^{-1}$
Specific root length	5000	5000	cm g^{-1}
Radiation use efficiency	0.7	0.7	g MJ^{-1}
Max leaf age	300	300	d

Table A5. Soil parameters assumptions in CUPPA-Tea.

Soil parameters	Tanzania	Kericho	Units
Organic carbon (cm depth, value)	15,1.61,70,0.7500,0	10,4.0,40,3.5,80,2.8120,1.3150,1.3300,1.3	%
Lower limit (PWP) (cm depth, value)	15,0.161,70,0.203,160,0.215,200,0.251,260,0.285,500,0.261	5,0.19,15,0.19,30,0.19,45,0.19,60,0.19,90,0.19,120,0.19,150,0.19,300,0.19	*v*/v water
Upper limit (FC)	15,0.266,70,0.288,160,0.286,200,0.308,260,0.340,500,0.296	5,0.29,15,0.29,30,0.29,45,0.29,60,0.29,90,0.29,120,0.29,150,0.29,300,0.29	v/v water
Soil description	NTRU: Sandy clay over clay	Medium sandy clay loam	–
Bulk density (cm depth, value)	15,1.24,70,1.24,160,1.21,200,1.01,260,1.01,500,1.17	5,1.35,15,1.35,30,1.36,45,1.36,60,1.36,90,1.37,120,1.38,150,1.38,300,1.38	g cm^{-3}
Humus mineralization factor	1	1	–
Soil albedo	0.13	0.13	–
Drainage constant	0.3	0.4	–
Runoff parameter	0	75	–
Root factor	15,1.000,70,1.000,160,1.000,200,1.000,260,1.000,500,1.000	5,1,15,1,30,0.819,45,0.607,60,0.607,90,0.368,120,0.202,150,0.111,300,0.111	–
Soil depth	500	300	cm
pH (cm depth, value)	15,4.6,70,4.2160,4.9200,5.8260,5.4500,6.0	5,4.01,15,4.05,30,4.05,45,4.05,60,4.05,90,4.05,120,4.05,150,4.05,300,4.05	–
Soil evapstage1 max	7.5	6	mm
Saturated water content (cm depth,value)	15,0.303,70,0.334,160,0.383,200,0.373,260,0.343,500,0.343	5,0.38,15,0.38,30,0.38,45,0.38,60,0.38,90,0.38,120,0.38,150,0.38,300,0.38	v/v water

Table A6. Assumptions used for the financial N response curves (KSh = Kenyan Shilling)*.

	Value	Unit
N content in urea	0.46	–
Green leaf value	45	KSh/kg green leaf
Labour rate	688	KSh/day
Transport cost	0.6	KSh/kg green leaf (0.005 US$ assumed 10 km distance)
Fertilizer application rate	280	kg/day
Exchange rate	108	KSh/USD
Assumed plucking rate	45	kg green leaf/day
Dry matter content	0.22	–
Fertilizer cost	1.01	USD/kg urea

* Profits were calculated when the total fertilizer cost was taken out from the value of revenue after harvesting costs. Revenue after harvesting costs was calculated as the subtraction of the harvesting cost from the value of made tea (all in USD ha^{-1}).

Table A7. Summary assumptions per N response included in CUPPA-Tea.

N responses	Assumptions
N application and urea hydrolysis	- Fertilizer is uniformly incorporated into the topsoil layer - N released by the hydrolysis of urea is added to the soil ammonium pool - Any urea remaining after 21 days is assumed to be hydrolysed
N movement	- No upward loss from the top layer occurs by this process - Only movement of nitrate and urea are considered - ammonium is assumed not to be transported - Movement of NO_3 and urea is dependent on water movement from one layer to the next. A simple cascading approach is used in which N lost from one layer is added to the one below - When the conc. of NO_3 falls to 1 mg kg^{-1} no further leaching from that layer occurs.
Plant N concentration	- Critical N content (TCNP) below which growth will be reduced - Minimum N content (TNMC) below which N content never falls - An index of deficiency relating the actual concentration (TANC) of above ground biomass to TMNC and TCNP used to determine the effect of N on plant growth
N uptake	- In case the soil profile's potential N supply, is greater than the crop N demand, then an N uptake factor is calculated and used to reduce the N uptake from each layer to the level of demand
N exudation	- Under conditions of luxury N uptake (TANC>TCNP), exudation of organic compounds can occur - This exuded N is added back to the fresh organic N pool and can be further mineralized and made available to the plant again
N mineralization	- The model starts with a crop residue C/N ratio of 40 - Initial FOM(L) contains: 20% carbohydrates, 70% cellulose and 10% lignin - Decay rates: 0.2 for carbohydrates, 0.05 for cellulose and 0.095 for lignin - 0.02 is the N requirement for microbial decay of a unit of FOM(L) - Potential humus mineralization rate: $8.3*10^{-5}$
N nitrification	- A 'capacity index' introduces a lag effect if conditions in the previous 2 days have been unfavorable for nitrification - The potential nitrification rate is independent of soil type - Nitrification is null at 4.5 ≥pH ≥9.0
N denitrification	- Calculations are only done when soil water content exceeds field capacity, soil temperature is >5 °C and nitrate concentration is >1 mg kg^{-1} soil

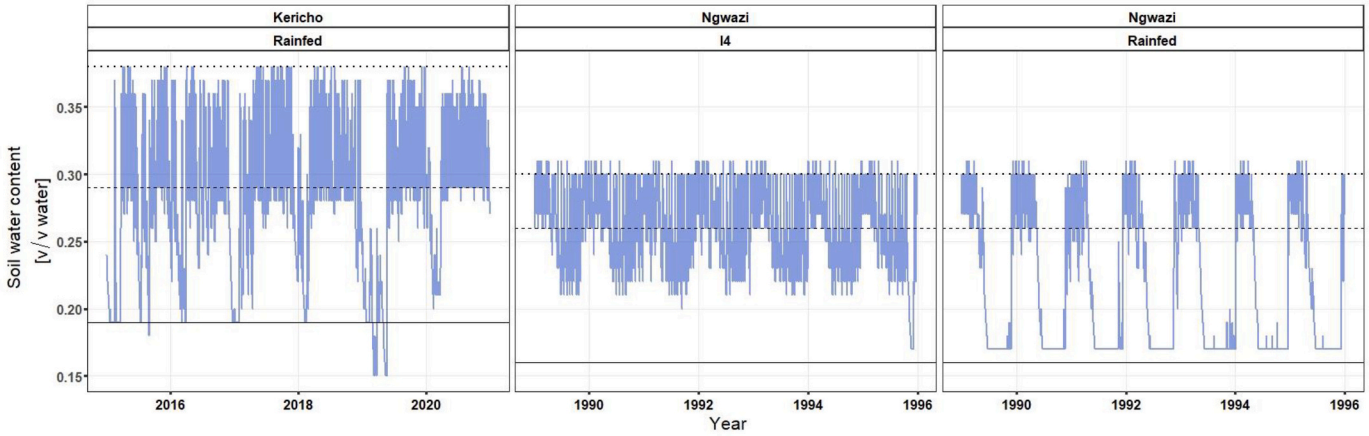


Fig. A2. Daily simulated soil water content at Kericho (under rainfed conditions at the top 15 cm) and at Ngwazi (under rainfed and I4 treatment at the top 25 cm). Solid line shows the permanent wilting point, dashed line the field capacity and dotted line is the saturated water content.

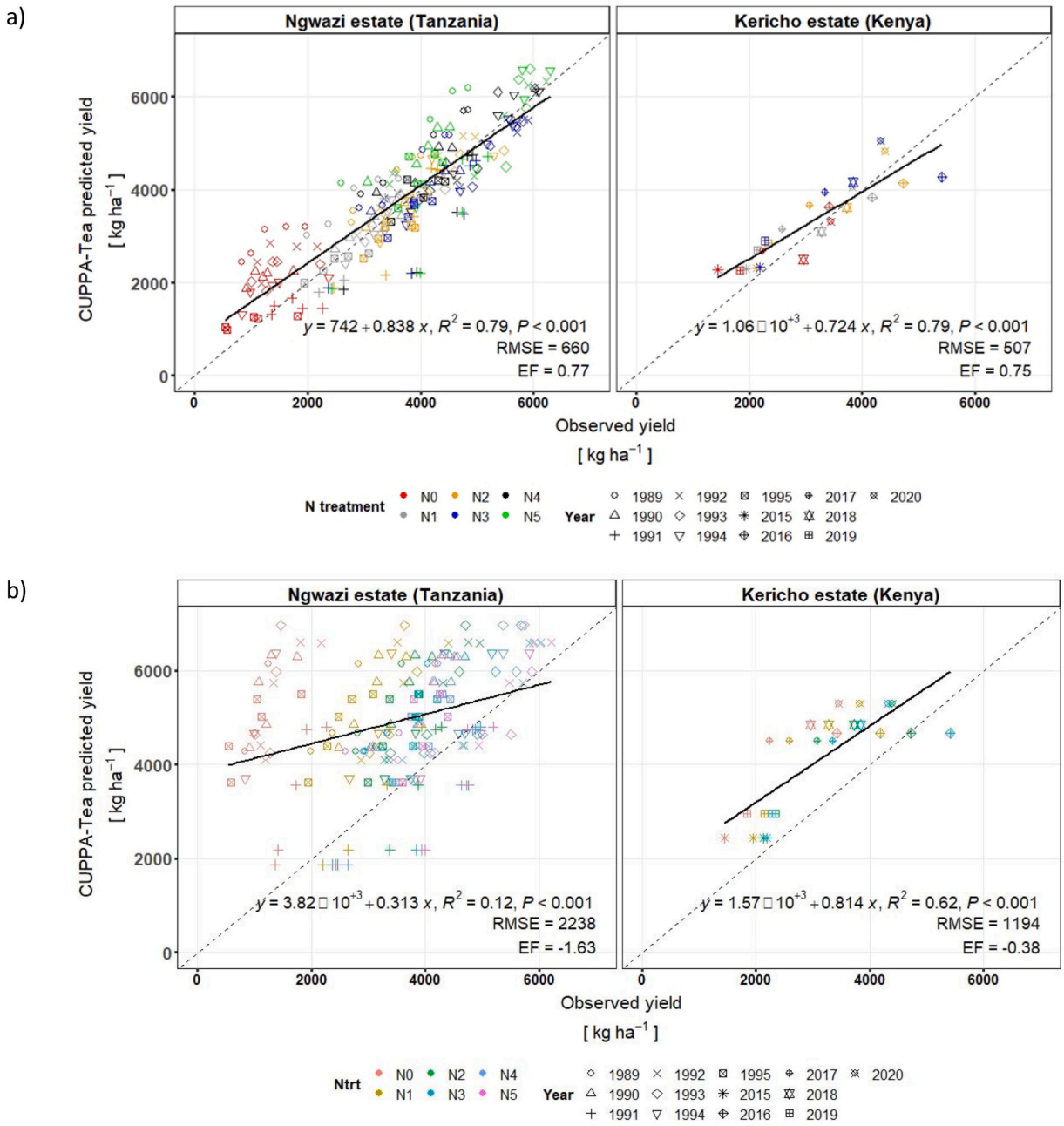


Fig. A3. Comparison of CUPPA-Tea goodness of fit for Ngwazi and Kericho when the N routine is a) turned on and b) turned off (Dashed line: 1:1; RMSE: root mean square error; EF: Modelling efficiency; shapes indicate year and colors N treatment).

Appendix B. Appendix

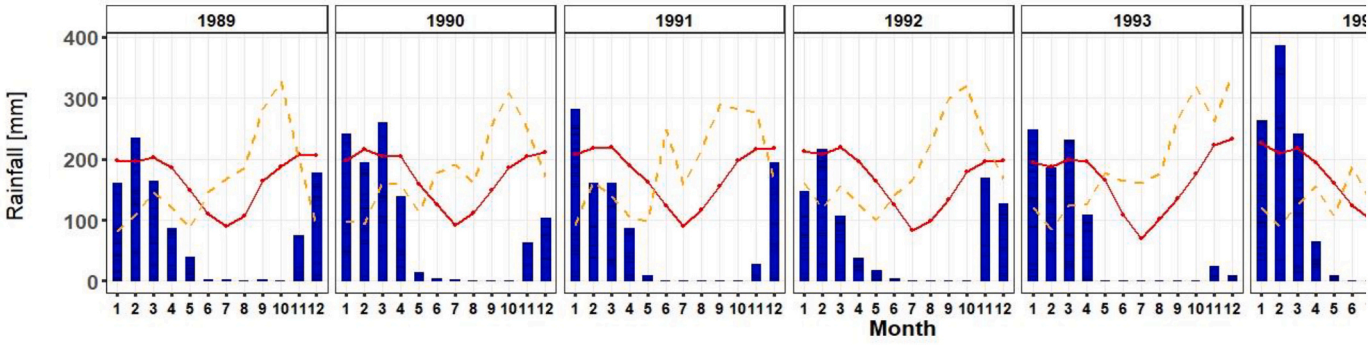


Fig. B1. Monthly rainfall (blue bars), mean temperature (red line) and mean solar radiation (orange dashed line) at Ngwazi tea estate (Tanzania). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

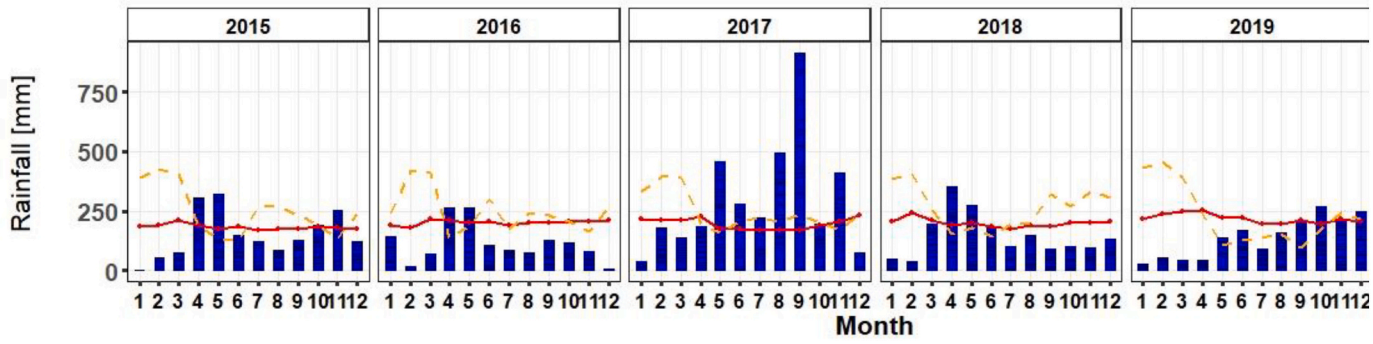


Fig. B2. Monthly rainfall (blue bars), mean temperature (red line) and mean solar radiation (orange dashed line) at Kericho tea estate (Kenya). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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Giannitsopoulos, Michail L.; Burgess, Paul J.; Sakrabani, Ruben; Holden, Ann; Saini, Helen ...

2023-12-01
Elsevier
https://doi.org/10.1016/j.agsy.2023.103754
Giannitsopoulos ML, Burgess PJ, Sakrabani R, et al., (2023) Modelling the effects of soil organic content and pH on the yield responses of tea to nitrogen fertilizer. Agricultural Systems, Volume 212, December 2023, Article Number 103754

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