Nutrient saturation of crop monocultures and agroforestry indicated by nutrient response efficiency

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Original Article

Received: 22 June 2020 / Accepted: 7 December 2020 / Published online: 19 December 2020
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Abstract Efficient use of nutrients is a key requisite for a sustainable intensification of agriculture in order to meet the increasing global crop demand while minimizing deleterious environmental impacts. Agroforestry systems exhibit tree–crop interactions, which potentially contribute to nutrient-efficient agro-ecosystems. Our goal was to determine whether the conversion from cropland monocultures to alley-cropping agroforestry increases nutrient response efficiency (NRE), the ability of plants to convert available nutrients into biomass. We found that crop yield, plant-available nutrients and NRE were comparable between agroforestry and monocultures, but the trees in agroforestry had high NRE, contributing to nutrient retention of the agroforestry systems as a whole. The unimodal relationship of the crops’ NRE with plant-available nutrients suggests that NRE values were beyond optimum in both agroforestry and monoculture indicating nutrient saturation. This indicates that fertilizer inputs can be reduced (or optimized) without sacrificing crop yield or profit. Based on the NRE curves, we assessed that a reduction of plant-available N by 50% would lead to a decrease in crop yield by 17% and a concomitant increase in N response efficiency by 67%, whereas a similar reduction of plant-available P would lead to a decrease in crop yield by 8% with an increase in P response efficiency by 83%. An optimized fertilization to achieve such lower levels of plant-available nutrients will have beneficial effects on nutrient retention and redistribution. Optimizing fertilizer input will make alley-cropping agroforestry a productive and profitable agro-ecosystem that contributes to an ecologically sustainable agriculture.

Keywords Environmentally sustainable agriculture · Alley-cropping agroforestry · Cropland monoculture · Soil nutrient stock · Soil organic carbon stock

Introduction

Global food production has increased in the past decades, following the demands of a growing world population (Food and Agriculture Organization of the United Nations 2015). Concomitantly, fertilizer use has increased disproportionately with productivity, resulting in decreasing fertilizer use efficiency and...
deleterious effects on the environment as a consequence of high loads of nitrogen and phosphorus (Tilman et al. 2002; Foley et al. 2005; Rockström et al. 2009). The dependency on pesticides and fertilizers common in conventional cropland monocultures is a major contributor to biodiversity loss (Geiger et al. 2010), groundwater pollution, global warming (Ward et al. 2014), $\text{N}_2\text{O}$-related ozone depletion (Ravishankara et al. 2009) and potential depletion of oxygen in the oceans (Handoh and Lenton 2003).

To meet the increasing global crop demand while minimizing environmental impacts, efficient use of nutrients is a key consideration, i.e. by maintaining or increasing yields on existing croplands while substantially lowering the use of fertilizers (Tilman et al. 2002, 2011; Foley et al. 2011). Improving the efficiency with which nutrients are converted into crop yield requires evaluation criteria of land-use systems that go beyond the traditional dose–response curves of fertilizer-yield relationships (Cerrato and Blackmer 1990). One important index is the nutrient response efficiency (NRE) = nutrient use efficiency (yield or biomass production per unit nutrient uptake) $\times$ nutrient uptake efficiency (nutrient uptake per unit available nutrient in the soil), or simply the ratio of yield or biomass production to plant-available nutrients in the soil (Bridgham et al. 1995). The NRE relationship with increasing nutrient availability depicts a unimodal curve (Electronic supplementary material Fig. 1). At low availability of a soil nutrient, NRE is also low, indicating nutrient limitation on productivity. As the nutrient availability increases, NRE increases towards an optimum, indicating high nutrient response with high productivity. When nutrient availability increases beyond this point, NRE declines and productivity levels off. A further increase in nutrient availability results in only minimal additional biomass gain and the ecosystem becomes nutrient-saturated (e.g. Pastor and Bridgham 1999; Hiremath and Ewel 2001; Schmidt et al. 2015). Maximizing productivity through chronic large fertilizer applications potentially leads to nutrient saturation and low NRE (e.g. Keuter et al. 2013) which, in turn, can decrease nutrient retention in biomass and in the soil, and ultimately increase nutrient losses and their negative environmental impacts (e.g. Hoeft et al. 2014).

Converting current monoculture-dominated agriculture into environmentally sustainable agriculture will require not only a focus on productivity and profitability, but also on other ecosystem functions that enhance human well-being (Rockström et al. 2017). In many parts of the world, agroforestry systems are multifunctional systems, delivering important ecosystem functions (e.g. provision of fuel, water or soil fertility regulation, gas/climate regulation, organism habitat) that monocultures do not or minimally provide. These functions render services such as soil and water quality, water availability, and mitigation of climate change and biodiversity losses (Jose 2009; Tscharntke et al. 2011). Crops produced in agroforestry are less affected by fungal pathogens and show similarly low mycotoxin concentrations in grains compared to those in monocultures (Beule et al. 2019). Additionally, modelling studies have suggested that across Europe, agroforestry has the potential to yield greater biomass than separate cultivation of crops and trees, especially where trees and crops were complementary in the use of light (Graves et al. 2007). Agroforestry systems can be equally or more profitable compared to cropland monocultures, depending on bio-economic factors such as subsidies and timber value (Graves et al. 2007). A recent pan-European analysis concluded that conversion towards multifunctional agroforestry systems would be favoured if their real value for society were reflected, e.g. through payments for ecosystem services (Kay et al. 2019).

In contrast to cropland monocultures, agroforestry systems support several mechanisms that can contribute to efficient nutrient cycling. Both trees and crops can profit from nutrient redistribution, e.g. crops, because of the nutrients added via litterfall and turnover, and the trees, because they take up nutrients through their roots below the crop rooting zone (Jose et al. 2000a, 2008; Cardinael et al. 2015b). Such complementary use of nutrients, or facilitation, occurs in the transition zone where crops and trees interact. However, combining trees and crops will only be beneficial if the effects of complementary nutrient use exceed competitive effects (Cannell et al. 1996), such as competition for soil mineral N (Jose et al. 2000a), water (Jose et al. 2000b) and light (Pardon et al. 2018). Complementary use of nutrients has been shown in a Canadian poplar–barley agroforestry system as a result of different depths in nutrient acquisition between trees and crops (Thevathasan and Gordon 1997). Furthermore, trees planted on former
agricultural soil increased soil N, P and K contents as well as nutrient turnover rates (Tsonkova et al. 2012) possibly due to pumping effect of tree roots that take up nutrients from deep soil and return them to topsoil via litterfall. In agroforestry systems, trees are commonly not or less fertilized than crops (Jose et al. 2000a; Cardinael et al. 2015a), however, it is presently unknown whether agroforestry systems are more nutrient-efficient compared to monocultures (Cardinael et al. 2015b).

Alley-cropping agroforestry systems, consisting of alternating rows of crops and short rotation coppice, are relatively easy to establish on monoculture cropland and have the advantage that with an optimal row spacing, farming techniques similar to monocultures can be applied. For farmers engaged in monocultures, this makes alley-cropping agroforestry a potentially attractive alternative. Several experimental alley-cropping systems have been established in the last decade in Germany (e.g. Langenberg et al. 2018; Swieter et al. 2018). The present study was conducted at three of these sites with contrasting soil characteristics (Table 1). Each of these sites had a cropland monoculture and a converted alley-cropping agroforestry treatment, all owned and managed by farmers. The conversion from cropland monocultures to agroforestry systems occurred 6 to 9 years prior to this study. An economic analysis conducted at two of these three sites showed that alley-cropping agroforestry was a profitable alternative, because the reduced income from crop production, a result of the smaller area under cropping, was offset by income generated by wood (Langenberg et al. 2018).

Our first objective was to determine changes in nutrient availability, crop productivity, and NRE between monoculture and alley-cropping agroforestry systems, with consideration of various distances from the tree row. For this objective, we tested the hypothesis that plant-available nutrients in the soil will be higher in crop alleys than in monocultures, based on the expected complementary use of nutrients between tree and crop rows in the alley-cropping systems. Our second objective was to determine the NRE curves along gradients of plant-available N, P and K across sites as indicators of whether these agro-ecosystems are nutrient-limited, at optimum efficiency or display nutrient saturation. Such curves can be used to optimize nutrient inputs in agro-ecosystems. We hypothesized that in both cropland monoculture and agroforestry systems, the NRE of the crops will fall in the nutrient saturation segment, as both crops in agroforestry and monocultures receive similar high fertilization rates and production practices, resulting in comparably high yield and low NRE for both crop rows and monoculture. Our study provides the first multi-site evaluation of alley-cropping agroforestry and cropland monocultures, using NRE as the main criterion, which can aid to improve strategies in optimizing nutrient acquisition efficiency in agro-ecosystems as well as in formulating policies geared towards more environmentally sustainable agricultural production.

Materials and methods

Site description and experimental design

Our study was conducted at three sites (Electronic supplementary material Fig. 2): Dornburg (11° 39’ O, 51° 01’ N Thuringia, Calcaric Phaeozem soil), Wendhausen (10° 38’ O, 52° 20’ N, Lower Saxony, Vertic Cambisol soil) and Forst (14° 38’ O, 51° 47’ N, Brandenburg, Gleyic Cambisol soil). Each site had an agroforestry system with an alley-cropping structure (i.e. alternating rows of crops and short rotation coppice; Electronic supplementary material Fig. 2) and an adjacent cropland monoculture. The agroforestry system was established by planting rows of fast-growing trees on the same area of monoculture such that at each site both the monoculture, being the reference land use, and the converted agroforestry area had the same management history. At all sites, the alley-cropping system consisted of 48-m wide fertilized rows of crops alternated with 12-m wide unfertilized rows of trees (Electronic supplementary material Fig. 2). Crop rotations included wheat (Triticum aestivum), barley (Hordeum vulgare) and rapeseed (Brassica napus) (Table 1). All agroforestry tree rows at the three sites consisted of poplar clone max 1 (Populus nigra × Populus maximowiczii), and were harvested 4 to 7 years after their establishment in the winter of 2013 or 2014 (Table 1). During our study years (2016 and 2017), tree age was between 2 and 4 years after their first cut and trees were 3 to 7-m high. The total annual atmospheric N deposition was 13–15 kg N ha⁻¹ yr⁻¹ for the agroforestry tree row.
and 11–13 kg N ha\(^{-1}\) yr\(^{-1}\) for the agroforestry crop row and monoculture (Umweltbundesamt 2018).

In the fall of 2015, we established four replicate plots at each site in both agroforestry and monoculture systems (Electronic supplementary material Fig. 2). Each replicate plot in the agroforestry spanned from the tree row into the crop row with four sampling locations: within the tree row (2.25 m from the crop edge) and at 1 m, 4 m and 7 m from the tree row (i.e. 3 sites × 4 replicate plots × 4 sampling locations = 48 sampling locations), whereas each replicate plot in monoculture was sampled at the plot’s center (i.e. 3 sites × 4 replicates = 12 sampling locations) (Electronic supplementary material Fig. 2). Grain yield was additionally sampled at 24 m from the tree row (crop row center). Replicate plots were 30 m × 30 m

Table 1 Management practices and climatic characteristics at the three sites of cropland agroforestry and adjacent cropland monocultures in Germany in 2016 and 2017

| Soil type (site)          | Year of establishment of agroforestry system | First harvest of trees in agroforestry | Age of trees (year) since first harvest during study years 2016 and 2017 | Crop rotation | Fertilizer application in 2016 (kg ha\(^{-1}\) yr\(^{-1}\)) | Fertilizer application in 2017 (kg ha\(^{-1}\) yr\(^{-1}\)) | Mean annual temperature (°C) | Annual precipitation (mm) |
|--------------------------|---------------------------------------------|---------------------------------------|------------------------------------------------------------------------|---------------|---------------------------------------------------------|---------------------------------------------------------|----------------------------|---------------------------|
| Calcaric Phaeozem (Dornburg) | 2007                                        | Winter 2014                           | 2–3                                                                    | Summer barley (2016) | N: 45                                                    | N: 105                                                   | 10.8 (2016)     | 531 (2016)             |
|                          |                                             |                                       |                                                                        | Winter rapeseed (2017)      | P: 19.8                                                  | P: 19.5                                                  | 10.9 (2017)     | 648 (2017)             |
|                          |                                             |                                       |                                                                        | Winter wheat               | K: 37.4                                                  | K: 97.2                                                  |               |                         |
| Vertic Cambisol (Wendhausen) | 2008                                        | Winter 2013                           | 3–4                                                                    | Winter rapeseed (2016)      | N: 221                                                   | N: 162                                                   | 10.3 (2016)     | 505 (2016)             |
|                          |                                             |                                       |                                                                        | Winter wheat               | P: 0                                                     | P: 0                                                     | 10.3 (2017)     | 819 (2017)             |
|                          |                                             |                                       |                                                                        | Winter barley              | K: 0                                                     | K: 0                                                     |               |                         |
| Gleyic Cambisol (Forst)   | 2010                                        | Winter 2014                           | 2–3                                                                    | Winter wheat (2016)         | N: 122                                                   | N: 86.4                                                  | 10.3 (2016)     | 593 (2016)             |
|                          |                                             |                                       |                                                                        | Winter barley              | P: 33.7                                                   | P: 15.1                                                  | 10.3 (2017)     | 621 (2017)             |
|                          |                                             |                                       |                                                                        | Corn                       | K: 51.6                                                   | K: 48.9                                                  |               |                         |

The same fertilization rates were applied to both the agroforestry crop row and monoculture. Agroforestry tree rows were unfertilized. Management data were provided by farmers; meteorological data were taken from Deutscher Wetterdienst (German Meteorological Service 2020)
(agroforestry) and 10 m × 10 m (monocultures), separated with a minimum distance of 30 m (agroforestry) and 10 m (monoculture).

General soil characteristic and plant-available nutrients

Soil bulk density, pH, organic C (SOC), total N, effective cation exchange capacity (ECEC) and base saturation were determined once during the growing season in 2016 for each sampling location. Bulk density was determined in the top 0.3 m using the core method (Blake and Hartge 1986). Soil samples for pH, SOC and ECEC were taken with an auger from the top 0.3 m, air-dried and sieved through a 2-mm sieve. Soil pH was measured in distilled water with a soil-to-water ratio of 1:4. The SOC and total N were measured using a CN analyser (Elementar Vario EL; Elementar Analysis Systems GmbH, Hanau, Germany). Soil samples with pH ≥ 6.0 were acid-fumigated prior to SOC analysis to remove carbonates (Harris et al. 2001). The ECEC was determined by percolating the soils with unbuffered 1 mol L⁻¹ NH₄Cl and the percolates were analysed for exchangeable elements (Ca, Mg, K, Na, Mn, Al, and Fe) using an inductively coupled plasma-atomic emission spectrometer (ICP-AES, iCAP 6300 Duo View ICP Spectrometer, Thermo Fischer Scientific GmbH, Dreieich, Germany). Base saturation was determined as the percentage of base cations on the ECEC. The exchangeable K was used as an index of plant-available K (Schmidt et al. 2015; Waring et al. 2015). As ECEC, including exchangeable K, does not vary substantially in consecutive years, we present plant-available K for 2016 only. Stocks of SOC and N were calculated from their concentrations using the measured average bulk density of 1.19 Mg m⁻³ for Calcaric Phaeozem soil, 0.89 Mg m⁻³ for Vertic Cambisol soil, and 1.28 Mg m⁻³ for Gleyic Cambisol soil.

Our index of plant-available N in the top 0.05-m depth was assessed using net N mineralization rates (Hart et al. 1994) from in situ incubations of intact soil cores for 7 days. As N uptake by roots is excluded in the in situ-incubated soil cores, the difference in mineral N before (T0) and after incubation (T1) has been referred to as plant-available N (Hart et al. 1994). Net N mineralization was measured monthly at each sampling location during the growing seasons of 2016 and 2017. Soil cores were extracted in the field with prepared bottles of 0.5 mol L⁻¹ K₂SO₄. Concentrations of extracted NO₃⁻ and NH₄⁺ were measured with continuous flow injection colorimetry (SEAL Analytical AA3, SEAL Analytical GmbH, Norderstedt, Germany). Plant-available N for the entire growing season at each sampling location was calculated as the mean of monthly net N mineralization rates multiplied by the number of days of the growing season of the crops (from germination to harvest) or trees (whole year), added with the atmospheric N deposition and N fertilization rate (the latter only for the agroforestry crop row and monoculture; Table 1).

Plant-available P in the top 0.05-m depth was assessed as the sum of resin-exchangeable P and bicarbonate-extractable P (Tiessen and Moir 1993; Cross and Schlesinger 1995). These were determined monthly at each sampling location during the growing seasons of 2016 and 2017. Concentrations of resin-exchangeable and bicarbonate-extractable P were determined using the ICP-AES (see above). The index of plant-available P for the entire growing period at each sampling location was calculated as the mean of the monthly measurements during the crops’ or trees’ growing period.

The amount of plant-available nutrients (N, P and K) in the soil was converted from mass basis to area basis. In order to compare the same soil mass for both land uses at each site, and to avoid the interference of bulk density changes with land-use change, we used the average soil bulk density of the monoculture plots (as the reference land use), as mentioned above. All statistical analyses first considered all sampling locations of the agroforestry crop rows (see below). However, as we were also interested on the aggregated measure for the agroforestry crop row as a whole, the plant-available nutrients in each replicate plot at each site were weighted based on the various measured distances within the crop row. We first tested auxiliary data on plant-available nutrients between 7 m and 24 m distances from the tree row and found no difference between these distances. Hence, the weighting factors that we used for plant available-nutrients were: 2.5:24 for 1-m distance, 3:24 for 4-m distance, and 18.5:24 for 7 and 24-m distance. The weighting factors for grain yield were 2.5:24 for 1 m, 3:24 for 4 m, 6.5:24 for 7 m and 12:24 for 24 m. These weighting factors were derived from the widths within the crop row that were represented by the sampled
distances, e.g. 1 m crop row represented a width ranged from 0 m (edge of the tree row) to 2.5 m (distance to tree row), which was 2.5 m of the 24 m (or 2.5:24) covered by our sampling locations (Electronic supplementary material Fig. 2).

Above-ground biomass production and nutrient response efficiency

Harvested grain yield was measured in July or August of 2016 and 2017, using a small harvester (plot combine), within an area of 17.5 m² at each sampling location. Tree leaf litter was measured bi-weekly from September to November of 2016 and 2017 at all sampling locations of the agroforestry sites using collection baskets with 0.14-m² area. To determine the tree woody biomass at all tree rows of the agroforestry sites, a site- and year-specific allometric equation 

\[
\text{woody dry mass} = a \times \text{stem diameter}^b
\]

with \(a\) and \(b\) as constants derived from the relationship between woody dry mass and stem diameter, Verwijst and Telenius (1999) was fitted to the stem diameter and biomass of 25 trees, sampled to cover the diameter range found at each site. Annual woody biomass production of trees in 2016 and 2017 was calculated as the difference between standing woody biomass between two consecutive years. The above-ground biomass production for the tree row was the sum of wood and leaf litter production. For the agroforestry crop row and monoculture, grain yield (excluding crops’ straw) was used for the NRE calculation as yield is the parameter of farmers’ interest. The grain yield of the sampling locations within the agroforestry crop row was also weighted (as explained above) to get a value for the whole crop row in each replicate plot at each site.

The NRE is calculated as grain yield (for crops) or above-ground biomass production (for trees) ÷ plant-available nutrients in the soil (Bridgham et al. 1995). To assess an index for plant-available nutrients, we measured a consistent depth interval across land uses or management systems. Measuring plant-available nutrients for the entire soil profile is neither necessary nor practical (Hiremath and Ewel 2001; Keuter et al. 2013; Schmidt et al. 2015; Waring et al. 2015). Similarly, NRE does not constitute a nutrient budget but serves as an indicator of the status of an agroecosystem, allowing assessment of whether it is nutrient limited, at optimum efficiency or nutrient saturated (Bridgham et al. 1995). We used the crops’ NRE to assess whether the resource efficiency in the agroforestry crop row was comparable, larger (prevailing tree–crop complementarity) or lower (suggesting tree–crop competition) than in the monoculture at each site. The agroforestry tree row, having inherently different productivity than the crops, were not statistically compared with the crops. Additionally, we assessed the relationships of the crops’ NRE with gradients of plant-available nutrients across sites (see “Statistical analysis” section below), where sites represented a soil fertility gradient (i.e. total N, SOC, ECEC, texture, Table 2) and different crop management (e.g. fertilization rates, Table 1).

Leaf-litter nutrient input and root density

Input of nutrients from leaf litter at all sampling locations of the agroforestry sites (i.e. within the tree row and at various distances from the tree rows) was calculated as the mass of leaf litter per area multiplied by the nutrient concentrations, analyzed from the collected leaf litter. Total N concentration in leaf litter was measured after drying and grinding of samples, using the CN analyzer mentioned above. Total P and K concentrations of the leaf litter samples were measured using the ICP-AES (see above) after pressure digestion in concentrated HNO₃.

For root quantification, we took soil cores of 0.6-m length and 65-mm in diameter with three subsamples per sampling location at the sites with Calcaric Phaeozem and Vertic Cambisol soils during the growing season of 2017. The soil cores were divided into depth intervals of 0–0.1 m, 0.1–0.2 m, 0.2–0.4 m and 0.4–0.6 m. The soils were washed carefully and all roots ≥10-mm length were collected and dried at 70 °C for 3 days. Dry root mass was expressed per unit area for the top 0.3-m depth and the subsoil of 0.3–0.6 m.

Statistical analysis

For comparison of plant-available nutrients, NRE and productivity at each site, we first tested whether there was a difference in soil texture among sampling locations; texture is a management- or land use-independent indicator to ascertain comparability of soil conditions between agroforestry and monoculture plots at each site (e.g. de Blécourt et al. 2013; Schmidt...
Table 2  Soil biochemical and physical properties, measured within 0–0.3-m depth in 2016, at the three sites of cropland agroforestry (AF) and adjacent cropland monocultures in Germany

| Soil type (site)         | pH (1:4 soil–H₂O-ratio) | Total N (kg m⁻²) | Organic C (kg m⁻²) | C:N ratio | Effective cation exchange capacity (mmol kg⁻¹) | Ca saturation (%) | K saturation (%) | Mg saturation (%) | Na saturation (%) | Base saturation (%) | Texture (% sand/silt/clay) |
|-------------------------|--------------------------|------------------|--------------------|------------|------------------------------------------------|------------------|-----------------|------------------|------------------|----------------------|-------------------------|
| Calcaric Phaeozem (Dornburg) |                          |                  |                    |            |                                                |                  |                 |                  |                  |                      |                         |
| AF tree row             | 6.5 ± 0.1c               | 0.64 ± 0.03a     | 6.18 ± 0.48a       | 9.6 ± 0.3a | 152 ± 5b                                      | 84.5 ± 0.6b      | 5.7 ± 0.5b      | 8.6 ± 0.3a      | 0.4 ± 0.1a       | 99.2 ± 0.1a          | 4b/76a/20b             |
| AF crop row             | 6.7 ± 0.0b               | 0.59 ± 0.01a     | 5.13 ± 0.12a       | 8.7 ± 0.1b | 160 ± 2b                                      | 85.8 ± 0.5b      | 5.1 ± 0.2b      | 8.1 ± 0.1a      | 0.4 ± 0.0a       | 99.3 ± 0.3a          | 4b/71a/25b             |
| Monoculture             | 7.9 ± 0.1a               | 0.56 ± 0.07a     | 4.64 ± 0.73a       | 8.1 ± 0.4b | 590 ± 101a                                    | 92.6 ± 1.5a      | 1.9 ± 0.4a      | 5.4 ± 1.1a      | 0.1 ± 0.0a       | 100.0 ± 0.0a         | 11a/51b/38a            |
| Vertic Cambisol (Wendhausen) |                          |                  |                    |            |                                                |                  |                 |                  |                  |                      |                         |
| AF tree row             | 7.1 ± 0.3a               | 0.71 ± 0.03a     | 6.82 ± 0.33a       | 9.7 ± 0.1a | 363 ± 77a                                      | 92.7 ± 1.5a      | 2.2 ± 0.3a      | 4.8 ± 1.1a      | 0.2 ± 0.1a       | 99.9 ± 0.0a          | 18ab/47a/35a           |
| AF crop row             | 7.4 ± 0.1a               | 0.70 ± 0.01a     | 6.58 ± 0.08a       | 9.5 ± 0.1ab| 386 ± 45a                                      | 93.4 ± 0.7a      | 2.1 ± 0.2a      | 4.2 ± 0.5a      | 0.2 ± 0.0a       | 99.9 ± 0.0a          | 18b/44a/38a            |
| Monoculture             | 7.4 ± 0.0a               | 0.72 ± 0.05a     | 6.16 ± 0.10a       | 8.7 ± 0.5b | 316 ± 8a                                      | 91.5 ± 0.6a      | 2.5 ± 0.3a      | 5.7 ± 0.4a      | 0.2 ± 0.1a       | 99.9 ± 0.0a          | 27a/29b/44a            |
| Gleyic Cambisol (Forst) |                          |                  |                    |            |                                                |                  |                 |                  |                  |                      |                         |
| AF tree row             | 7.1 ± 0.1a               | 0.47 ± 0.01a     | 4.12 ± 0.27ab      | 8.8 ± 0.7a | 57.9 ± 7.1a                                   | 80.0 ± 2.0a      | 2.5 ± 0.6a      | 16.5 ± 1.4ab    | 0.5 ± 0.1a       | 99.4 ± 0.2a          | 61a/32a/7a            |
| AF crop row             | 7.0 ± 0.0a               | 0.45 ± 0.01a     | 4.18 ± 0.12a       | 9.3 ± 0.2a | 57.0 ± 3.4a                                   | 81.2 ± 0.9a      | 2.3 ± 0.3a      | 15.2 ± 0.8b     | 0.7 ± 0.2a       | 99.4 ± 0.0a          | 67a/24a/9a            |
| Monoculture             | 7.1 ± 0.0a               | 0.41 ± 0.02a     | 3.48 ± 0.20b       | 8.5 ± 0.2a | 54.3 ± 6.5a                                   | 77.1 ± 2.2a      | 1.2 ± 0.1a      | 20.4 ± 2.2a     | 0.6 ± 0.2a       | 99.4 ± 0.1a          | 67a/24a/9a            |

At each site, mean ± SE (n = 4) with different letters indicate significant differences between AF tree and crop rows and monoculture (one-way ANOVA with Tukey HSD test at P ≤ 0.05)
et al. 2015). If there was no difference, further analysis was done without a covariate; if otherwise, clay content was used as a covariate, as in the case of the Calcaric Phaeozem soil (Table 1). Using clay content as a covariate results in the exclusion of confounding effects caused by textural differences, which affect other soil parameters such as ECEC (e.g. Schmidt et al. 2015). Each parameter was first tested for equality of variances with a Levene test and for normal distribution with a Shapiro–Wilk test. If these two conditions were met, differences between groups (i.e. sampling locations or land uses) were tested with a one-way ANOVA followed by Tukey HSD test. If normal distribution was not met, a Kruskal–Wallis test with multiple comparison extension was used. If equality of variances was not met, a one-way T test pairwise comparison with a Holm-correction was used. For the site with Calcaric Phaeozem soil, we used ANCOVA with clay content as a covariate, and checked for normality and homogeneity of variance of the model residuals using diagnostic plots. If normality and variance homogeneity of residuals were not met, we used the Generalized Linear Model (GLM) with a Gamma distribution. If still the GLM residuals did not show normality and variance homogeneity, the model (either ANCOVA or GLM Gamma) with the diagnostic plot closely approximating these conditions was chosen. We accepted statistical differences as significant at $P$ values $\leq 0.05$. We refrained from comparing NRE between crops and trees due to their inherent productivity differences, but reported the trees’ NRE for its added value in the agroforestry system.

The mathematical relationships of NRE along the range of plant-available nutrients across sites were fitted using a least-squares approach on the Michaelis–Menten equation (Bridgham et al. 1995).

$$NRE = \frac{(\text{Nutrient}_{\text{av}} - \text{Nutrient}_{\text{min}}) \cdot \text{Production}(P)_{\text{max}}}{(\text{Nutrient}_{\text{av}} - \text{Nutrient}_{\text{min}}) + \text{Nutrient}_{\text{av}} 0.5 P_{\text{max}}}$$

(1)

Nutrient$_{\text{av}}$ is the availability of an essential nutrient, Nutrient$_{\text{min}}$ is the nutrient availability at zero production and Nutrient$_{\text{av}} 0.5 P_{\text{max}}$ is the nutrient requirement at half of the maximum production $P_{\text{max}}$. This relationship depicts the change of productivity or NRE along a gradient of nutrient availability (Electronic supplementary material Fig. 1). We used the best fit curves of Eq. 1 across sites (Fig. 1) to assess potential changes in crop yield as well as N and P response efficiencies when plant-available N and P are reduced by 50%. For this, we set the plant-available nutrient to ½ of its observed mean. We then calculated the corresponding NRE according to the estimated
equations presented in the caption of Fig. 1. We did not do this for K since its availability strongly differs with sites (Fig. 1c). All analyses were conducted using R version 3.5.1.

Results

Plant-available nutrients and nutrient response efficiency

Tree-mediated nutrient redistribution reached far into the crop rows, illustrated by nutrient inputs from tree leaf litter and roots that were measurable even at 7-m distance from the tree row (Electronic supplementary material Fig. 3). In the crop rows of the agroforestry systems, N, P and K inputs from tree leaf litter decreased with increasing distance to the tree rows (Electronic supplementary material Fig. 3a, b, c). In addition, tree root mass within the top plow layer (0–0.3 m, Electronic supplementary material Fig. 3d) and subsoil (0.3–0.6 m, Electronic supplementary material Fig. 3e) decreased with distance from the tree row to the crop row.

Plant-available N, P and K under crops at different distances from the tree row were not different, with the exception of lower plant-available N at the 1 or 4 m distance compared to the 7 m distance (Calcaric Phaeozem or Vertic Cambisol in 2017; Electronic supplementary material Table 1; \( P \leq 0.01 \)). Crops in the agroforestry crop row (weighted by sampled distances) and monoculture did not differ in plant-available N, P or K (Table 3), except for plant-available P in Vertic Cambisol soil in 2016 and 2017 (\( P \leq 0.03 \)).

The crops’ NRE did not differ between agroforestry crop row (weighted by sampled distances) and monoculture with the exception of a higher N response efficiency in the agroforestry crop row at the Gleyic Cambisol soil in 2017 (Table 4; \( P = 0.01 \)). These comparable NREs of crops in the two systems were a result of the similar grain yields between agroforestry crop row and monoculture treatments (with only slightly diminished yield at 1 m crop row; Electronic supplementary material Table 2) as well as their analogous soil nutrient availability, described above. The agroforestry tree rows displayed large NRE, caused by their high biomass productivity (Electronic supplementary material Table 2) with generally comparable levels of nutrient availability as those in the agroforestry crop row (Table 3 and Electronic supplementary material Table 1).

The best-fit curves for NRE of agroforestry crop row and monoculture along the ranges of plant-available nutrients across sites showed a monotonous decrease with increases in plant-available nutrients (\( P \leq 0.01 \) for N, P and K; Fig. 1a, b, c). This corresponded to a condition where plant-available nutrients in the soil are higher than optimum efficiency (Electronic supplementary material Fig. 1)—nutrient saturation was strongest for plant-available P (Fig. 1b). We assessed that a reduction in plant-available N by 50% would lead to a decrease in crop yield by 17% and an increase in N response efficiency by 67%, whereas a similar reduction of plant-available P would lead to a decrease in crop yield by 8% and an increase in P response efficiency by 83%.

Soil characteristics

With the exception of the higher SOC in the agroforestry crop row compared to the monoculture at the site with Gleyic Cambisol soil (\( P = 0.04 \)), the general soil characteristics did not differ between the agroforestry tree or crop rows and monocultures (\( P > 0.05–0.91 \); Table 2). Furthermore, at the site with Calcaric Phaeozem soil, the higher soil C:N ratio, lower pH and lower ECEC of the agroforestry tree or crop rows compared to the monoculture (\( P = 0.01–0.04 \)) were associated with lower clay contents at the agroforestry system (\( P = 0.01 \)).
Table 3  Plant-available N, P and K measured within the top 0.05-m soil depth at the three sites of cropland agroforestry (AF) and adjacent cropland monocultures in Germany during the growing season of 2016 and 2017

| Soil type (site)          | Plant-available N (g N m\(^{-2}\) growing season\(^{-1}\)) | Plant-available P (g P m\(^{-2}\)) | Plant-available or exchangeable K (g K m\(^{-2}\)) |
|--------------------------|------------------------------------------------------------|-----------------------------------|--------------------------------------------------|
|                          | 2016            | 2017            | 2016            | 2017            | 2016            | 2017            |
| Calcaric Phaeozem (Dornburg) |         |                  |                  |                  |                  |                  |
| AF tree row              | 9.6 ± 3.6a     | 9.0 ± 1.2a     | 12.6 ± 0.9a     | 10.4 ± 0.6a     | 20.3 ± 2.2a     |
| AF crop row              | 14.5 ± 4.3a    | 41.7 ± 12.0a   | 12.7 ± 0.4a     | 10.3 ± 0.4a     | 18.8 ± 1.0a     |
| Monoculture              | 13.4 ± 3.3a    | 63.0 ± 29.4a   | 11.8 ± 0.9a     | 10.1 ± 0.7a     | 22.6 ± 2.5a     |
| Vertic Cambisol (Wendhausen) |         |                  |                  |                  |                  |                  |
| AF tree row              | 3.2 ± 0.3b     | 5.9 ± 1.6b     | 7.7 ± 0.5b      | 9.7 ± 0.8b      | 12.4 ± 0.2a     |
| AF crop row              | 82.9 ± 22.9a   | 33.6 ± 1.9a    | 8.4 ± 0.7b      | 9.2 ± 1.2b      | 12.9 ± 0.6a     |
| Monoculture              | 48.6 ± 17.4ab  | 36.5 ± 7.8ab   | 11.2 ± 0.6a     | 13.8 ± 0.7a     | 13.8 ± 1.1a     |
| Gleyic Cambisol (Forst)  |         |                  |                  |                  |                  |                  |
| AF tree row              | 3.8 ± 0.8b     | 4.7 ± 0.8b     | 14.1 ± 1.1a     | 7.9 ± 0.8a      | 3.6 ± 1.1a      |
| AF crop row              | 33.3 ± 10.3a   | 11.4 ± 0.3a    | 13.0 ± 0.6a     | 7.6 ± 0.3a      | 3.1 ± 0.8a      |
| Monoculture              | 19.3 ± 1.5ab   | 12.1 ± 0.8a    | 12.4 ± 0.7a     | 7.3 ± 0.3a      | 1.7 ± 0.3a      |

Values for agroforestry crop row are weighted with the measured distances within the crop row. At each site, mean ± SE (n = 4) with different small letters indicates significant differences between AF tree and crop rows and monoculture (one-way ANOVA with Tukey HSD test at \(P \leq 0.05\)).

Table 4  Nutrient response efficiency (NRE) at the three sites of cropland agroforestry (AF) and adjacent cropland monocultures in Germany during the growing season of 2016 and 2017

| Soil type (site)          | N response efficiency (g DM m\(^{-2}\) yr\(^{-1}\)/g N m\(^{-2}\) growing season\(^{-1}\)) | P response efficiency (g DM m\(^{-2}\) yr\(^{-1}\)/g P m\(^{-2}\)) | K response efficiency (g DM m\(^{-2}\) yr\(^{-1}\)/g K m\(^{-2}\)) |
|--------------------------|-------------------------------------------------------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
|                          | 2016            | 2017            | 2016            | 2017            | 2016            | 2017            |
| Calcaric Phaeozem (Dornburg) |         |                  |                  |                  |                  |                  |
| AF tree row              | 169.6 ± 45.86   | 175.4 ± 14.8    | 91.5 ± 13.3     | 149.5 ± 18.3    | 56.7 ± 7.2      | 77.7 ± 8.2      |
| AF crop row              | 42.9 ± 10.6a    | 9.2 ± 2.5a      | 35.0 ± 0.6a     | 26.4 ± 1.1a     | 23.9 ± 2.0a     | 14.7 ± 1.6a     |
| Monoculture              | 45.9 ± 9.8a     | 9.4 ± 2.8a      | 44.4 ± 2.8a     | 37.0 ± 3.1a     | 24.0 ± 3.3a     | 16.8 ± 1.8a     |
| Vertic Cambisol (Wendhausen) |         |                  |                  |                  |                  |                  |
| AF tree row              | 590.3 ± 86.1    | 473.4 ± 152.6   | 239.2 ± 29.5    | 223.3 ± 22.0    | 146.5 ± 12.3    | 171.5 ± 7.5     |
| AF crop row              | 4.2 ± 0.9a      | 18.9 ± 1.5a     | 35.5 ± 4.1a     | 70.4 ± 8.1a     | 22.9 ± 1.9a     | 48.3 ± 1.9a     |
| Monoculture              | 10.2 ± 2.6a     | 22.2 ± 4.1a     | 33.5 ± 2.5a     | 52.1 ± 1.5a     | 27.5 ± 2.4a     | 52.9 ± 3.9a     |
| Gleyic Cambisol (Forst)  |         |                  |                  |                  |                  |                  |
| AF tree row              | NA              | 283.4 ± 39.6    | NA              | 162.9 ± 19.0    | NA              | 415.9 ± 79.0    |
| AF crop row              | 26.1 ± 6.1a     | 45.5 ± 2.6a     | 50.0 ± 3.0a     | 68.5 ± 4.1a     | 241.3 ± 43.9a   | 201.2 ± 46.2a   |
| Monoculture              | 27.3 ± 4.9a     | 30.8 ± 0.6b     | 41.8 ± 6.4a     | 51.6 ± 5.9a     | 368.1 ± 118.2a  | 265.0 ± 76.1a   |

Values for agroforestry crop row are weighted with the measured distances within the crop row. At each site, mean ± SE (n = 4) with different small letters indicates significant differences between agroforestry crop row and monoculture (\(P \leq 0.05\)); AF tree row, being functionally different from the crops, was not statistically compared with the crops’ NRE but evidently showed large NRE at all sites. NA—data on woody biomass production was not available.
Table 2). We accounted for this variation in soil texture by including clay content as a covariate in all further statistical analyses of the Calcaric Phaeozem site.

Discussion

No effects of agroforestry on soil fertility in young systems

The potential of agroforestry systems to increase SOC and nutrient stocks have been reported in other studies (Tsonkova et al. 2012; Cardinael et al. 2015a; Pardon et al. 2017). In contrast to these studies, SOC and N stocks as well as base saturation in our alley-cropping agroforestry systems remained generally comparable with the cropland monocultures (Table 2). Most studies reporting increases in SOC and nutrient stocks have been conducted on relatively mature systems (Pardon et al. 2017), while the agroforestry systems that we studied were established 6 to 9 years prior to our study. Furthermore, systems from which increases in SOC and nutrient stocks were reported often had an inherently lower soil fertility (e.g. post-mining sites; Tsonkova et al. 2012), and with that a high potential for improvement, compared to the relatively fertile soils at our sites (with high ECEC and > 99% base saturation; Table 2). Our findings were in line with earlier observations that only agroforestry systems with a tree component older than 15 years display significant increases in SOC and nutrient stocks (Pardon et al. 2017). Nonetheless, at our relatively young agroforestry systems, we observed considerable tree–crop row interactions, such as tree litter-nutrient inputs and tree roots at the crop rows (Electronic supplementary material Fig. 3). These are critical prerequisites for possible increases in SOC and nutrient stocks with age of agroforestry systems (e.g. Dhillon and Van Rees 2017).

High fertilizer inputs override potentially beneficial tree–crop interactions

Despite the observed complementary interactions between tree and crop rows, we did not observe differences in plant-available N, P and K in the soil between the monoculture and various distances within the crop rows (Electronic supplementary material Table 1). This is in contrast to the expectation of higher plant-available nutrients in the crop row. This seemed puzzling at first, especially as changes in available nutrients occur more rapidly than changes in total nutrient stocks (Jose et al. 2000a; Pardon et al. 2017). However, a comparison of the quantities of nutrients redistributed by tree litterfall within the first few meters of the crop rows (Electronic supplementary material Fig. 3a, b, c) with the amounts of nutrients added by fertilizers (Table 1) illustrated that the high levels of fertilizer application in the agroforestry crop row probably overrode any potential facilitation effect. Other competitive tree–crop row interactions were more obvious. The reduction in the crop’s grain yield at 1-m distance compared to the farther distances from the tree rows (Electronic supplementary material Table 2) was probably caused by competition between trees and crops for resources other than nutrients, such as light (Pardon et al. 2018) or water (Jose et al. 2000b). However, this decrease in the crop’s grain yield close to the trees was compensated by the higher production of crops at greater distances from the tree rows (Swieter et al. 2018) (Electronic supplementary material Table 2).

The large NRE of the tree rows (Table 4) indicate that agroforestry systems have an overall advantage in NRE compared to cropland monocultures, particularly in fertile soils where the tree component is productive. The large NRE of trees indicated high nutrient retention and, given the complementary interactions of the tree and crop rows (Electronic supplementary material Fig. 3), will foster redistribution of nutrients within the system. For agroforestry systems with a tree component managed as a short rotation coppice, woody biomass production will be moderated during the first years following establishment or the first year following harvest. We expect that during such earlier periods of tree (re-)growth, the overall NRE of agroforestry systems may not be higher than the cropland monocultures. However, considering that the trees in our alley-cropping systems are being harvested every 4 to 7 years (Table 1) and that their NRE were already substantial after 2 to 4 years from cutting (Table 4), the overall NRE of these agroforestry systems for the tree growing cycle of 4 to 7 years may surpass the NRE of cropland monocultures. Our field-based assessment of NRE is crucial for developing policies geared towards optimizing the use of...
Reduced fertilization largely increases NRE with only small reduction in crop yield

The monotonous decrease in NRE of agroforestry crops and monocultures with increasing ranges in plant-available N, P and K levels across sites (Fig. 1a, b, c) illustrated that the levels of these nutrients in the soil mostly exceeded optimal values in both monocultures and alley-cropping systems (Pastor and Bridgham 1999; Fig. 1 with Electronic supplementary material Fig. 1 as insets). This supports our hypothesis that the NRE of the crops in both agroforestry and monocultures display nutrient saturation. These results were in stark contrast to unmanaged, mixed deciduous forest stands in central Germany, wherein the P and K response efficiencies were at the optimal level (Schmidt et al. 2015). However, the available P and K levels within the same 0.05-m depth of that forest site were much lower than in our present fertilized agroforestry crops rows and monocultures (Table 1). Our results provide enticing indications that plant-available nutrients, especially N and P, can be reduced in both agroforestry crop rows and monocultures with only small reductions in crop yield. The obvious way to reduce plant-available N, P and K in these agroforestry and monoculture systems is by reducing fertilization rates. Based on inherent mechanisms that contribute to a more efficient acquisition and recycling of nutrients in agroforestry systems compared to monocultures (i.e. tree leaf litter-nutrient input and a permanent deep root system of the trees; Electronic supplementary material Fig. 3), we anticipate that agroforestry systems will perform better than cropland monocultures under reduced fertilizer application. This emphasizes the need for an ecosystem level index of resource efficiency such as NRE that, unlike fertilizer use efficiency, takes into account the inherent provision of nutrients by the soil under adapted management, e.g. agroforestry. A reduced fertilization regime may also enhance the microbial cycling and retention processes of N, via mineralization (Carpenter-Boggs et al. 2000) and N immobilization (Hoeft et al. 2014). Earlier studies (Jose et al. 2000a; Cardinael et al. 2015a) have speculated, based on observed increases in SOC and nutrient concentrations, that a reduction of the fertilization regime to crops in agroforestry systems is promising. Although nutrient redistribution via tree litterfall in agroforestry systems varied spatially (Electronic supplementary material Fig. 3) and temporally, as it is controlled by productivity of and distance to the tree rows (Pardon et al. 2017), precision farming techniques can be implemented to compensate for tree row-induced nutrient gradients (Cardinael et al. 2015a). Reducing the costs of fertilizer inputs may further increase the profitability of agroforestry systems (Langenberg et al. 2018) compared to monocultures, particularly when crop yield is maintained (i.e. at optimum NRE). Optimization of the already high NRE in agroforestry systems (Table 4) through a reduced fertilization regime (e.g. for N, Fig. 1a) will reduce the risk of N losses (Tilman et al. 2002) and improve ecosystem services (Hoeft et al. 2014; Rockström et al. 2017).

Conclusions

Our study demonstrated that the concept of NRE is useful to evaluate the nutrient status of agricultural systems across locations. NRE curves further allowed to detect potentials for optimizing fertilization rates and thus a more sustainable nutrient management. The shape of NRE curves depends on factors such as crop demand, the ability of the soil to mineralize and retain nutrients and, in the case of agroforestry, the amount of nutrients released from litterfall from the tree row. Alley-cropping agroforestry, aside from being a productive and profitable agro-ecosystem, may have additional ecosystem functions through redistribution of nutrients via leaf litterfall and tree roots (e.g. soil fertility regulation, water filtration, and gas/climate regulation), which can contribute to environmentally sustainable agricultural production. Future investigation should focus on economic valuation of these ecosystem functions as well as quantification of nutrient leaching losses and soil greenhouse gas fluxes for a holistic assessment of ecosystem functions of cropland agroforestry versus monocultures.

Acknowledgements Open Access funding enabled and organized by Projekt DEAL. This study was financed by the German Federal Ministry of Education and Research (BMBF) in the framework of the BonRes-SIGNAL project (funding codes: 031AS562A and 031B0510A). We thank Meike Hildgerdenaar and Christoph Büll for the collection of tree root data. We also wish to express thanks to Dirk Böttger, Andrea Bauer, Martina...
Knaust and Kerstin Langs for technical and laboratory support. We wish to also thank the two anonymous reviewers for their constructive comments on an earlier version of the manuscript.

**Author’s contribution** MS, MDC and EV designed the experiment and wrote the manuscript. MS, BK, JM, LG, AS and SS carried out the field and laboratory works. MS conducted the data analysis.

**Funding** Bundesministerium für Bildung und Forschung (031A562A/031B0510A).

**Availability of data and materials** All compiled data in this study are published in figures and tables. Detailed primary data are stored and published in the BonaRes DataCentre and available via the BonaRes Repository at [https://doi.org/10.20387/bonares-q82e-t008](https://doi.org/10.20387/bonares-q82e-t008).

**Code availability** Data analysis has been conducted using the free software R as described in the “Statistical analysis” section.

**Compliance with ethical standards**

**Conflict of interest** The authors declare no conflicts of interest.

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**References**

Beule L, Lehtsaar E, Rathgeb A, Karlovsky P (2019) Crop diseases and mycotoxin accumulation in temperate agroforestry systems. Sustainability 11:2925. [https://doi.org/10.3390/su1102925](https://doi.org/10.3390/su1102925)

Blake GR, Hartge KH (1986) Bulk Density. In: Klute A (ed) Methods of Soil Analysis: part 1—physical and mineralogical methods. American Society of Agronomy, Inc., Madison, pp 363–375

Bridgham SD, Pastor J, McIaugherty CA, Richardson CJ (1995) Nutrient-use efficiency: a Litterfall Index, a model, and a test along a nutrient-availability gradient in North Carolina Peatlands. Am Nat 145:1–21. [https://doi.org/10.1086/285725](https://doi.org/10.1086/285725)

Cannell MGR, Noordwijk MV, Ong CK (1996) The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. Agrofor Syst 34:27–31. [https://doi.org/10.1007/BF00129630](https://doi.org/10.1007/BF00129630)

Cardinael R, Chevallier T, Barthès BG et al (2015a) Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon—a case study in a Mediterranean context. Geoderma 259–260:288–299. [https://doi.org/10.1016/j.geoderma.2015.06.015](https://doi.org/10.1016/j.geoderma.2015.06.015)

Cardinael R, Mao Z, Prieto I et al (2015b) Competition with winter crops induces deeper rooting of walnut trees in a Mediterranean alley cropping agroforestry system. Plant Soil 391:219–235. [https://doi.org/10.1007/s11104-015-2422-8](https://doi.org/10.1007/s11104-015-2422-8)

Carpenter-Boggs L, Pikul JL, Vigil MF, Riedell WE (2000) Soil nitrogen mineralization influenced by crop rotation and nitrogen fertilization. Soil Sci Soc Am J 64:2038–2045. [https://doi.org/10.2136/sssaj2000.6462038x](https://doi.org/10.2136/sssaj2000.6462038x)

Cerrato ME, Blackmer AM (1990) Comparison of models for describing corn yield response to nitrogen fertilizer. Agron J 82:138–143. [https://doi.org/10.2134/agronj1990.000219620082000010030x](https://doi.org/10.2134/agronj1990.000219620082000010030x)

Cross AF, Schlesinger WH (1995) A literature review and evaluation of the. Helley fractionation: applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. Geoderma 64:197–214. [https://doi.org/10.1016/0016-7061(94)00023-4](https://doi.org/10.1016/0016-7061(94)00023-4)

de Blécourt M, Brumme R, Xu J et al (2013) Soil carbon stocks decrease following conversion of secondary forests to rubber (Hevea brasiliensis) plantations. PLoS ONE 8:e69357. [https://doi.org/10.1371/journal.pone.0069357](https://doi.org/10.1371/journal.pone.0069357)

Deutscher Wetterdienst (German Meteorological Service) (2020) Online data repository of recent and historic meteorological data. [ftp://ftp-cdc.dwd.de/climate_environment/CDC/observations_germany/climate/daily/kl/](ftp://ftp-cdc.dwd.de/climate_environment/CDC/observations_germany/climate/daily/kl/)

Dhillon GS, Van Rees KCJ (2017) Soil organic carbon sequestration by shelterbelt agroforestry systems in Saskatchewan, Can J Soil Sci 97:394–409. [https://doi.org/10.1139/cjss-2016-0094](https://doi.org/10.1139/cjss-2016-0094)

Foley JA, DeFries R, Asner GP et al (2005) Global consequences of land use. Science 309:570–574. [https://doi.org/10.1126/science.1111772](https://doi.org/10.1126/science.1111772)

Foley JA, Ramankutty N, Brauman KA et al (2011) Solutions for a cultivated planet. Nature 478:337–342. [https://doi.org/10.1038/nature10452](https://doi.org/10.1038/nature10452)

Food and Agriculture Organization of the United Nations (2015) FAO statistical pocketbook 2015: world food and agriculture. FAO, Rome

Geiger F, Bengtsson J, Berendse F et al (2010) Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. Basic Appl Ecol 11:97–105. [https://doi.org/10.1016/j.baae.2009.12.001](https://doi.org/10.1016/j.baae.2009.12.001)

Graves AR, Burgess PJ, Palma JHN et al (2007) Development and application of bio-economic modelling to compare silvooarable, arable, and forestry systems in three European countries, Ecol Eng 29:434–449. [https://doi.org/10.1016/j.ecoleeng.2006.09.018](https://doi.org/10.1016/j.ecoleeng.2006.09.018)

Handoh IC, Lenton TM (2003) Periodic mid-Cretaceous oceanic anoxic events linked by oscillations of the phosphorus and oxygen biogeochemical cycles. Glob Biogeochem Cycles. [https://doi.org/10.1029/2003GB002039](https://doi.org/10.1029/2003GB002039)
Harris D, Horwáth WR, van Kessel C (2001) Acid fumigation of soils to remove carbonates prior to total organic carbon or CARBON-13 isotopic analysis. Soil Sci Soc Am J 65:1853–1856. https://doi.org/10.2136/sssaj2001.1853

Hart SC, Stark JM, Davidson EA, Firestone MK (1994) Nitrogen mineralization, immobilization, and nitrification. In: Methods of soil analysis: part 2—microbiological and biochemical properties sssabookseries, pp 985–1018. https://doi.org/10.2136/sssabookser5.c42

Hiremath AJ, Ewel JJ (2001) Ecosystem nutrient use efficiency, productivity, and nutrient accrual in model tropical communities. Ecosystems 4:669–682. https://doi.org/10.1007/s10021-001-0036-x

Hoefl I, Keuter A, Quíñones CM et al (2014) Nitrogen retention efficiency and nitrogen losses of a managed and phytodiverse temperate grassland. Basic Appl Ecol 15:207–218. https://doi.org/10.1016/j.baae.2014.04.001

Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. Agrof Syst 76:1–10. https://doi.org/10.1016/j.agsy.2009.09.029

Jose S, Gillespie AR, Seifert JR et al (2000a) Defining competition vectors in a temperate alley cropping system in the midwestern USA: 3. Competition for nitrogen and litter decomposition dynamics. Agrof Syst 48:61–77. https://doi.org/10.1007/A1006241406462

Jose S, Gillespie AR, Seifert JR, Biehle DJ (2000b) Defining competition vectors in a temperate alley cropping system in the midwestern USA: 2. Competition for water. Agrof Syst 48:41–59. https://doi.org/10.1007/A1006289322392

Jose S, Allen SC, Naar PR (2008) Tree–crop interactions: lessons from temperate alley-cropping systems. In: Batish DR, Kohli RK, Jose S, Singh HP (eds) Ecological basis of agroforestry. CRC Press, Boca Raton, London, New York

Kay S, Graves A, Palma JHN et al (2019) Agroforestry is paying off—economic evaluation of ecosystem services in European landscapes with and without agroforestry systems. Ecosyst Serv 36:100896. https://doi.org/10.1016/j.ecoser.2019.100896

Keuter A, Hoefl I, Veldkamp E, Corre MD (2013) Nitrogen response efficiency of a managed and phytodiverse temperate grassland. Plant Soil 364:193–206. https://doi.org/10.1007/s11104-012-1344-y

Langenberg J, Feldmann M, Theuven L (2018) Alley cropping agroforestry systems: using Monte-Carlo simulation for a risk analysis in comparison with arable farming systems. Ger J Agric Econ 67:95–112

Pardon P, Reubens B, Reheul D et al (2017) Trees increase soil organic carbon and nutrient availability in temperate agroforestry systems. Agric Ecosyst Environ 247:98–111. https://doi.org/10.1016/j.agee.2016.07.018

Pardon P, Reubens B, Mertens J et al (2018) Effects of temperate agroforestry on yield and quality of different arable intercrops. Agric Syst 166:135–151. https://doi.org/10.1016/j.agsy.2018.08.008

Pastor J, Bridgham SD (1999) Nutrient efficiency along nutrient availability gradients. Oecologia 118:50–58. https://doi.org/10.1007/s004420050702

Ravishankara AR, Daniel JS, Portmann RW (2009) Nitrous oxide (N2O): the dominant ozone-depleting substance emitted in the 21st century. Science 326:123–125. https://doi.org/10.1126/science.1176985

Ravishankara AR, Daniel JS, Portmann RW (2009) Nitrous oxide (N2O): the dominant ozone-depleting substance emitted in the 21st century. Science 326:123–125. https://doi.org/10.1126/science.1176985

Rockström J, Steffen W, Noone K et al (2009) A safe operating space for humanity. Nature. https://doi.org/10.1038/461472a

Rockström J, Williams J, Daily G et al (2017) Sustainable intensification of agriculture for human prosperity and global sustainability. Ambio 46:4–17. https://doi.org/10.1007/s13280-016-0793-6

Schmidt M, Veldkamp E, Corre MD (2015) Tree species diversity effects on productivity, soil nutrient availability and nutrient response efficiency in a temperate deciduous forest. For Ecol Manag 338:114–123. https://doi.org/10.1016/j.foreco.2014.11.021

Swieter A, Langhof M, Lamerre J, Greef JM (2018) Long-term yields of oilseed rape and winter wheat in a short rotation alley cropping agroforestry system. Agrof Syst. https://doi.org/10.1007/s10457-018-0288-5

Thevathasan NV, Gordon AM (1997) Poplar leaf biomass distribution and nitrogen dynamics in a poplar-barley intercropped system in southern Ontario, Canada. Agrof Syst 37:79–90. https://doi.org/10.1023/A:1005853811781

Tiessen H, Moir JO (1993) Characterization of available P by sequential extraction. In: Carter MR, Gregorich EG (eds) Soil sampling and methods of analysis, vol 7. CRC Press, Boca Raton, pp 5–229

Tilman D, Cassman KG, Matson PA et al (2002) Agricultural sustainability and intensive production practices. Nature. https://doi.org/10.1038/nature01014

Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. Proc Natl Acad Sci 108:20260–20264. https://doi.org/10.1073/pnas.1116437108

Tscharntke T, Clough Y, Bhagwat SA et al (2011) Multifunctional shade-tree management in tropical agroforestry landscapes—a review. J Appl Ecol 48:619–629. https://doi.org/10.1111/j.1365-2664.2010.01939.x

Tsonkova P, Böhm C, Quinkenstein A, Freese D (2012) Ecological benefits provided by alley cropping systems for production of woody biomass in the temperate region: a review. Agrof Syst 85:133–152. https://doi.org/10.1007/s10457-012-9494-8

Umweltbundesamt (2018) Hintergrundbelastungsdaten Stickstoff (Background nitrogen loads). Online map service. https://gis.uba.de/website/depo1/

Verwijst T, Telenius B (1999) Biomass estimation procedures in tropical dry forest. Oecologia 178:887–897. https://doi.org/10.1007/s00442-015-3283-9

Ward DS, Mahowald NM, Kloster S (2014) Potential climate forcing of land use and land cover change. Atmos Chem Phys 14:12701–12724. https://doi.org/10.5194/acp-14-12701-2014

Waring BG, Becknell JM, Powers JS (2015) Nitrogen, phosphorus, and cation use efficiency in stands of regenerating tropical dry forest. Oecologia 178:12701–12724. https://doi.org/10.1007/s00442-015-3283-9

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