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Tree rows and grass-strips increase water availability in fruit tree-crop agroforestry systems on sloping land

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ABSTRACT

Soil water conservation in upland areas characterised by slopes is extremely challenging. Information about soil water availability and variability, which can guide appropriate soil water management, is often lacking, including for agroforestry (AF) which is considered a sustainable farming practice in these regions. This study aims to describe how soil water is distributed and how it impacts crop growth and yield in an agroforestry system.

Investigations were carried out in 2022–2023, in year 6 and 7 of an experiment wherein a fruit tree (mango and longan)-maize-grass treatment was compared to sole-maize in four replicates. Nine slope positions in each AF-plot were defined based on their distance from the tree rows, whilst three positions along the slope were selected in the sole-maize.

Available soil water content (ASWC) down to 60 cm depth varied between 14 and 141 mm and was up to 28 mm higher in the AF system than the sole-maize following rain events. Generally, the ASWC was lower downslope than upslope of the tree rows and declined more rapidly after rain events. During the early dry season, ASWC was higher in mango-AF but lower in longan-AF compared to sole-maize, whereas the opposite was true late in the dry season. Maize grain yield was consistently lower in the zone immediately downslope (1.0 ton ha^{-1}) than upslope (3.2 ton ha^{-1}) of tree rows, but the yield-reducing effect downslope decreased with increasing distance from the tree rows and grass-strips. Water was generally not limiting maize yields.

To conclude, ASWC was higher in AF than in sole-maize and increased more upslope than downslope of tree rows and grass strips immediately after rain events. The choice of tree species influenced ASWC in the dry season.

Abbreviations

AF	Agroforestry
ASWC	Available soil water content, soil water availability
BD	Bulk density
CEC	Cation exchange capacity
Cl	Clay content
DAS	Days after sowing
Fruit-maize-AF	Fruit tree-maize-grass agroforestry
HI	Harvest Index
Longan-AF	Longan-maize-grass agroforestry sub-treatment
Mango-AF	Mango-maize-grass agroforestry sub-treatment
PWP	Permanent wilting point
SC	Stone content
SDG	Sustainable Development Goal
Si	Silt content
SM	Sole-maize treatment
SOC	Soil organic carbon
VSW	Volumetric soil water

(continued on next column)

1. Introduction

Agroforestry (AF) can be defined as the integration of trees with crops and/or livestock within the same land area [1]. AF has the potential to effectively help reach the Sustainable Development Goals

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(SDGs), i.e. poverty reduction (SDG 1), hunger alleviation (SDG 2), climate action (SDG 13), and biodiversity conservation and sustainable land management (SDG 15) [2–4]. The contour hedgerow system is a common type of AF [5] used on sloping land in Asia [6,7], Africa [8], and South America [9]. In contour hedgerow systems, forage grass or woody species grown in strips or rows along the contour are intercropped with annual crops such as rice, maize, and cassava. Grass strips along the contour can provide several benefits such as contributing to soil conservation [10–12], improving farmers' livestock fodder access [8,13], and trapping and storing water [5].

Fruit tree plantation has expanded rapidly in the last decade, as seen in Vietnam [14]. There, it has replaced sole-cropping systems with annual crops such as maize, cassava, or sugarcane and it is occasionally combined with different crops in fruit tree-crop AF systems. The most commonly used fruit tree species in the region of this study are longan (*Dimocarpus longan* Lour.) and mango (*Mangifera indica* L.). The characteristic differences between mango [15–17] and longan [18–20] may affect resource competition and should therefore inform system design and management. Planting fruit trees requires high investment costs, and it takes 3–4 years for the trees to generate income [21]. Thus, the inclusion of annual crops and forage grass in fruit-crop-grass AF systems have amplified on the sloping land [22].

Appropriate system design and management of resource use and competition play an imperative role in achieving an economically and environmentally sustainable AF system. When assessing the effects of fruit-crop AF systems on crop performance on sloping land, maize yield has been found to decrease as fruit trees grow [8,12,21,24]. This is likely a result of competition from the trees and/or grass for light, water, and/or nutrients. In a previous study, we found that longan and mango trees affected light availability to the maize particularly on the downslope side of tree rows, but the effect was only important for yield in the areas closest to the trees and grasses, downslope grass-strips [25].

Available soil water content (ASWC) is an important factor for the growth and development of plants but can be a limiting factor for the grain yield of rain-fed crops [26,27]. The ASWC is particularly crucial on sloping land, since a greater slope gradient may result in larger surface or subsurface water flows, and soil erosion [28,29], which alters soil texture by predominantly eroding silt particles [30], and reduces soil depth [30], water infiltration rate [29], soil water [30,31], and water use efficiency [32]. These effects can subsequently reduce crop growth and yield [33]. In fruit-maize-grass AF, natural terrace formation [12] may increase infiltration and decrease runoff, thereby potentially increasing ASWC. The increased transpiration from the fruit trees increases the water consumption [34–36] and potential biomass production by the AF systems. Studies show that the water use from deeper soil layers by trees with deep roots [e.g. mango, 17] compete to a lesser degree with annual crops that have shallower roots than trees with shallow root systems [e.g. longan, 37]. However, differences in root distribution may be relatively small on shallow soil profile. Nevertheless, this could have consequences for water storage as the growth during the dry season may be influenced [38]. The trade-off between resource competition and crop productivity can be addressed by cropping system design and management [39]. The cropping system design should take advantage of current knowledge on the spatial-temporal distribution of ASWC and other resources [40]. However, to the best of our knowledge, the impact of the combination of fruit tree and grass strips on the spatial-temporal distribution of ASWC in sloping land has not yet been investigated.

The aim of this study was to describe the temporal and spatial distribution of ASWC and its importance for maize growth and production in a semi-mature, fruit-maize-grass agroforestry system on steep sloping land in subtropical conditions with much of the precipitation concentrated to the summer season. Three hypotheses were defined: 1) Fruit tree rows and grass strips enhance the available water for plant growth in agroforestry compared to that in sole-maize; 2) Soil water availability will be greater in nearby upslope zones of the tree rows than downslope, consistent with maize yield and biomass; and 3) mango trees, with their deeper root system, compete less for water during the maize season and support a higher plant available water in the shallow soil layers during the dry season than longan trees with shallower roots.

2. Materials and methods

2.1. Site description

The study was carried out over a two-year period (2022–2023) in a fruit-maize-grass AF experiment established in 2017 in a farmer's field in the Mai Son district, Son La province, Vietnam (21.10°N, 104.06°E; 566 masl) (Fig. 1). The average slope gradient is 21° and faces west-southwest. The soil is Acrisol and has a clay content of 18 %, 36 %, 42 %, and 25 % in the Ap-soil layer, B1, B2, and BC, respectively (Table S1). A detailed soil profile description was provided by Do et al. [12].

2.2. Field experiment, study design, and management

2.2.1. Field experiment

A randomised complete block design was used with two treatments (fruit-maize AF and sole-maize) and four replicates [12]. The fruit-maize AF system included longan (*Dimocarpus longan* L. 'PHM-99-1-1') and mango (*Mangifera indica* L. 'GL4') intercropped with maize (*Zea mays* L. 'PAC999Super') and guinea grass (*Panicum maximum* Jacq. 'Mombasa') and was compared with sole-maize system as control. The PAC999Super (Advanta Seeds) is a single-cross hybrid maize cultivar with a life cycle of about 105–115 days in the study area [41]. Plants were grown in single-species rows along contour lines. Longan and mango were planted in alternate rows at a density of 250 tree ha^{-1} (10 m × 4 m). Two grass rows (0.5 m apart) were planted below the fruit rows with 1 m between the fruit tree to the closest grass row. Trees and grass strips accounted for 30 % of the area at year 6 and 7 of the experiment in 2022 and 2023, when this investigation was conducted. Maize was sown in the blank alley from 1.2 m upslope of the tree trunks to 1.25 m downslope the centre of two grass strips (Fig. 2). The maize density was 71,000 plants ha^{-1} in sole-maize and in the alley of the AF treatment. Maize seeds were sown at a spacing of 0.7 m between rows and 0.3 m within rows, with two seeds per spot. After germination, thinning or transplanting were carried out to achieve the target population (i.e. alternating one or two plants per spot).

2.2.2. Study design

In this study, the fruit-maize AF was split into longan-maize-grass (longan-AF) and mango-maize-grass (mango-AF) sub-systems. Each sub-system was divided into 1 m wide zones according to their distance from the tree rows, with zones 1 to 4 upslope of the fruit trees (zone 5), grass (zone 6), and 7–9 downslope. The centres of zones 4 and 7 were 1.5 m and 1.25 m from the centre of zone 5 (tree) and the centre of zone 6 (grass), respectively (Fig. 3).

2.2.3. Experimental management

Maize was sown on 14 May and 16 June, after the application of NPK (5:10:3) basal fertiliser, and harvested on 18th September and 25th October in 2022 and 2023, respectively. The maize was weeded and then fertilised with urea and potassium at 6–7 leaves and silking stages. The seasonal amount of nutrients applied to the maize was 192 kg N, 18 kg P, 63 kg K, and 40 kg S ha^{-1} in sole-maize (Tables S4 and S5) following local practice and company recommendation. In the agroforestry system, 30 % less fertilisers were applied compared to sole-maize, reflecting the smaller maize area [25]. Emamectin was used to control fall armyworm (*Spodoptera frugiperda*) in both seasons. Additionally, other chemical compounds were sprayed to protect the fruit trees from pests and diseases, as recommended by local advisory (Tables S2 and S3). Fertilisers were applied to fruit trees but not the grass (Tables S4

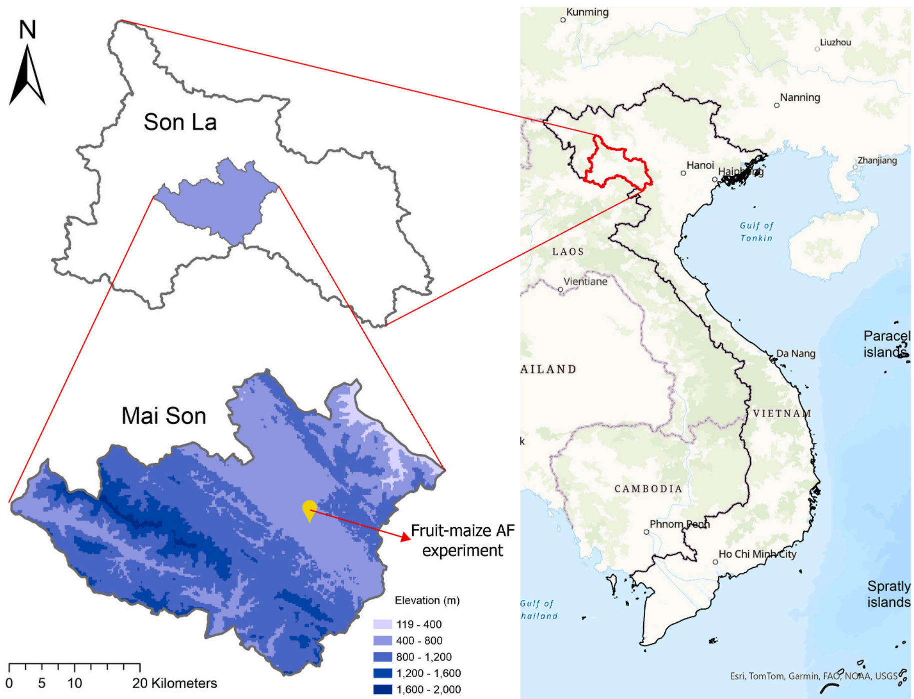

Fig. 1. Location of the fruit-maize-grass agroforestry (fruit-maize-AF) experiment in Mai Son district, Son La province, Vietnam.

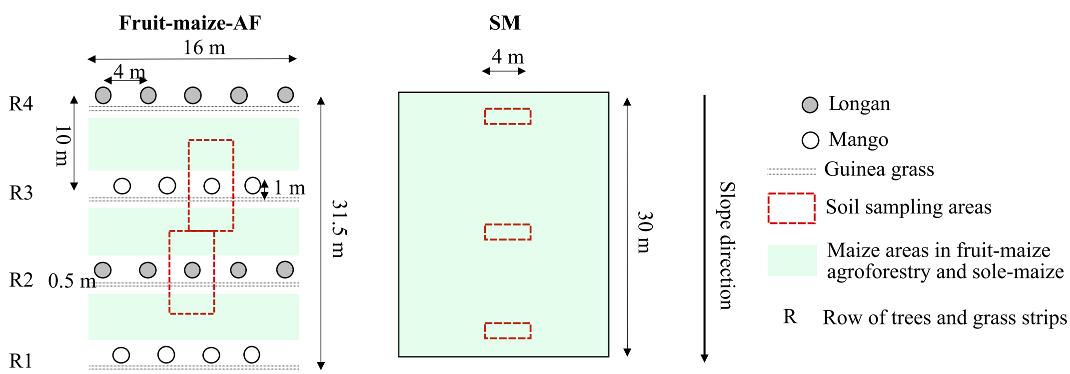

Fig. 2. Experiment design and data collection area of fruit-maize-grass agroforestry (fruit-maize-AF) and sole-maize (SM) treatment. Adjusted from Do et al. [12].

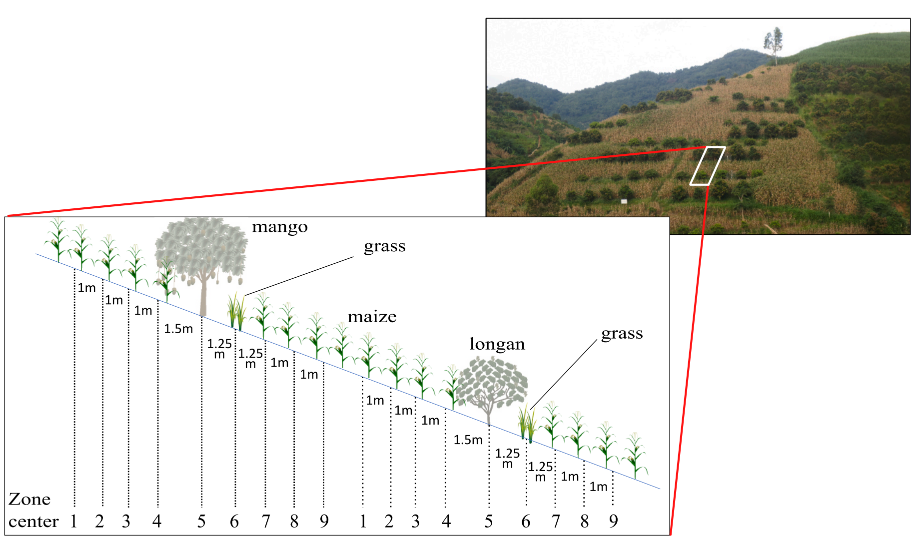

Fig. 3. Field trial layout and position of zones in longan-mango-maize-grass agroforestry experiment. Adjusted from Pham et al. [25].

and S5).

In the AF system, trees were pruned four times each season. The major pruning occurred in winter (November-early December) when farmers removed about 20 % of the canopy. Gentle pruning was carried out to manage twig density in summer (May–June) and autumn (August–September). After harvesting, all dead branches and fruited twigs were removed [25]. Farmers weeded twice during the maize season at the 6–7 leaf and silking stages, prior to fertiliser application. Additional weeding was carried out before and after the maize season in connection with land preparation to avoid both increasing the seed bank and damaging the perennial structures of the weeds (Tables S2 and S3).

2.3. Data collection

2.3.1. Weather data

Daily rainfall and average temperature data were collected from a mini-weather station (ATMOS 41, METER Group, Inc.) which was set up in the experiment. The total rainfall was 1376 mm, and 1200 mm, whilst the annual mean temperature was 22.0 °C and 22.9 °C in 2022 and 2023, respectively. The rainy season typically lasts from May to September, but in 2023, the rainy season started in June and consequently delayed the maize sowing (Fig. 4a). There was a dry spell in July 2022 when the maize was at the tasselling and silking stage. There was also a short dry spell in July 2023 when the maize had 7 to 10 leaves (Fig. 4b).

2.3.2. Available soil water by gravimetric method

Soil gravimetric water samples were taken down to 60 cm depth in 20 cm increments on 23 March, 20 June (6–7 leaves), 01 July (10–11 leaves), 13 July (silking stage), 29 September, and December 20, 2022. In 2023 samples were taken on 14 March, 12 July (3–4 leaves), 24 July (6–7 leaves), 09 August (10–11 leaves), 27 August (silking stage), and 11 December. All measurements were taken at least four days after any rainfall episode, except the measurements for the 10–11 leaves stage in both seasons and at silking in 2023 which were taken less than four days after rainfall. The soil depth sampled was based on Do et al. [12], who did not find any maize roots below 60 cm. However, grass and tree roots can be expected below this depth. The biomass samples were weighed before and after oven drying at 105 °C until no change was observed, respectively. The volumetric soil water content (VSW) was calculated from wet (W_{wet}) and dry (W_{dry}) soil samples (g) and soil bulk density (BD, g cm^{-3}) by Eq. (1) which was adjusted from FAO [42]. We collected BD samples (Table S6) from the topsoil of the different zones, as the terrace formation [12] may have affected soil characteristics, such as inducing soil organic carbon (SOC) accumulation and reducing BD, which could lead to different potential ASWC [43].

$$\text{VSW (mm)} = \text{BD} \times 1000 \times (W_{wet} - W_{dry}) / W_{dry} \quad (1)$$

Available soil water content (ASWC) was calculated as the difference between the soil water content at sampling and the permanent wilting point (PWP, mm) (Eq. (2)).

$$\text{ASWC (mm)} = \text{VSW} - \text{PWP} \quad (2)$$

The PWP of soil was calculated using a pedotransfer equation by Van den Berg et al. ([44], Eq. (3)). This was selected because it builds on a large set of international soil data that also includes similar soil types and similar tropical climates to those at the field sites (e.g. in China, Thailand, and Indonesia). The Van den Berg pedotransfer function also gave a high R^2 (Tables S7 and S8) when we tested the correlation against observed data for an Acrisol in the ISRIC [45] database, and this function was further recommended by Nguyen et al. [46].

$$\text{PWP} = 3.34 \times \text{Cl} \times \text{BD} + 1.04 \times \text{Si} \times \text{BD} \quad (3)$$

Where Cl is clay content (%), BD is bulk density (g cm^{-3}), and Si is silt content (%). The topsoil PWP value ranged from 143 to 154 mm in different zones of longan-AF, mango-AF, and sole-maize. It was higher in the subsoil (202 and 215 mm in B1 and B2 soil layers, respectively) than topsoil, consistent with the higher clay content.

2.3.3. Available soil water by moisture sensors

Five soil water sensors (TEROS 11, Meter Group, Inc.) were installed in zones 4, 6, 7 (at 10 cm depth) and zone 5 (at 10 and 30 cm depths) of the longan-AF and mango-AF sub-treatments (10 sensors in total) in one replicate (Fig. 3). The sensors in zone 5 were placed 0.3 m from the tree trunk along the contour, whilst the others were placed on a slope line with the respective tree and perpendicular to the tree row. The sensors were connected to data loggers to record water dynamics in the soil and used to support discussing the fluctuation of soil water. Data was downloaded monthly in 2022 and 2023. The soil water sensors were calibrated by taking gravimetric soil samples, measuring volumetric water content, and computing a linear regression between samples and sensor data [47].

2.3.4. Infiltration rate

To complement soil water content data, the infiltration rate was measured in the AF and SM plots in block 4 in October 2023. In this study, the quasi-steady infiltration rate was determined from the infiltration rate versus time and was considered as the observed field-saturated hydraulic conductivity. We selected above tree row (zone 4), tree row (zone 5), grass strip (zone 6), below grass strip (zone 7), and midway between two tree rows in each sub-treatment and one position in the middle of the sole-maize plot to measure soil water infiltration. The field saturated infiltration was measured using a one-ring method with rings of 109.4 mm inner diameter and 220 mm height. These were pushed 50 mm into the soil and 150 mm height of water was maintained. Three measurements were recorded with 30-min intervals after the infiltration rate had stabilised, and the average was taken as the saturated infiltration rate. In zones 4, 6, and 7 in AF, and middle of SM plot, there were 4 replicated measurement points per zone which were each 1m apart. In zone 5 (the tree row), we measured 3 positions (12 replicates in total) including around the trees' trunk, the midway point between 2 trees (2m from trees' trunks), and the intermediate point (1m

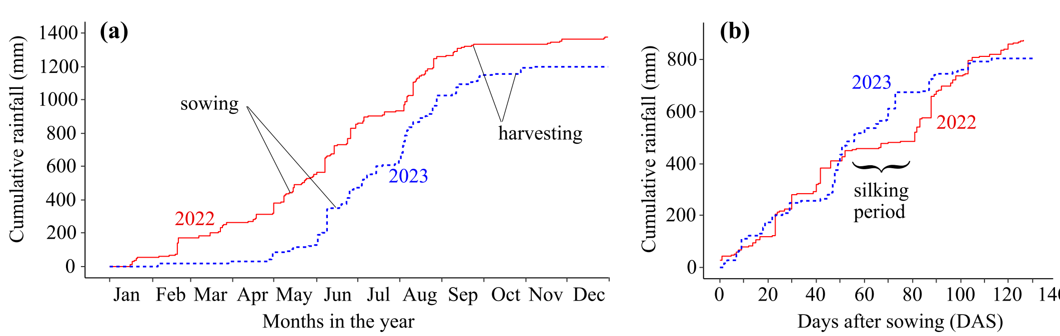

Fig. 4. Cumulative daily rainfall in fruit-maize-grass agroforestry experiment for the whole year in both 2022 and 2023 (a), and during the two maize seasons (b). The silking period was the same for both seasons in (b).

from trees' trunks) to capture the effects of management of harvesting and fertilising.

2.3.5. Tree/crop growth and yield

Fruit tree growth (height, trunk diameter at 10 cm height, and canopy width) was recorded quarterly in March, June, September, and December. Fresh fruit yield data was obtained for every tree (kg tree^{-1}) for both species. The growth in 2022 was published by Pham et al. [25]. Since 2022, the average longan tree's height, stem diameter, and canopy width had increased from 2.0 to 2.3 m, 6.7–9.3 cm, and 2.1–2.5 m, respectively. For the mango trees, these measurements increased from 3.1 to 3.5 m, 11.2–14.3 cm, and 2.8–3.1 m, respectively. Thus, the mango trees were significantly larger than the longan trees (Table S9). The longan and mango trees bore an average of 9.7 kg and 6.1 kg, respectively, of fresh fruit per tree in 2023, which was more than in 2022.

The guinea grass biomass was cut and harvested when the grass reached 1–1.2 m height, for a total of 15 times over the two seasons. The grass biomass production peaked in the rainy seasons (July 2022 and August 2023) and was low in the dry season (November to March) (Fig. S1). The cumulative dry harvested biomass of the grass was approximately 4 tons ha^{-1} year^{-1} and did not differ between longan-AF and mango-AF sub-treatments.

Maize was harvested from an area of 3.5 m^2 in all maize zones in the AF system to measure the fresh grain yield and above-ground biomass. In the sole-maize system, we collected maize samples from three (top, middle, and bottom) 3.5 m^2 positions in each replicate plot. Subsamples of grain and stover were taken and air-dried to determine the dry matter content, whereafter the dry grain yield (ton ha $^{-1}$), above-ground biomass (ton ha^{-1}), and harvest index (HI) were calculated. The presented yields were adjusted to the actual maize area in each zone in the AF system. The whole AF system crop yield for the 5 first years of the experiment was reported by Do et al. [48].

2.4. Data analysis

Data was analysed, and visualised using MS Excel 365 (Version 2405), R (Version 4.2.3) R-Studio (2023.12.0.369), and Inkscape 1.3. Analysis of variance (ANOVA, lmerTest package [49]) F-test was conducted to test for significant differences between (sub-)treatments, and between zones in longan-AF and mango-AF sub-treatments using a linear mixed model (lme4 package [50]) with fixed effect of time, treatment, and zone, and random effect of block. Box-Cox transformation was used if necessary to reach the assumption of heterogeneity of variances. A pairwise comparison using the emmean function [51] with the Tukey adjustment method was used to test the differences between categories.

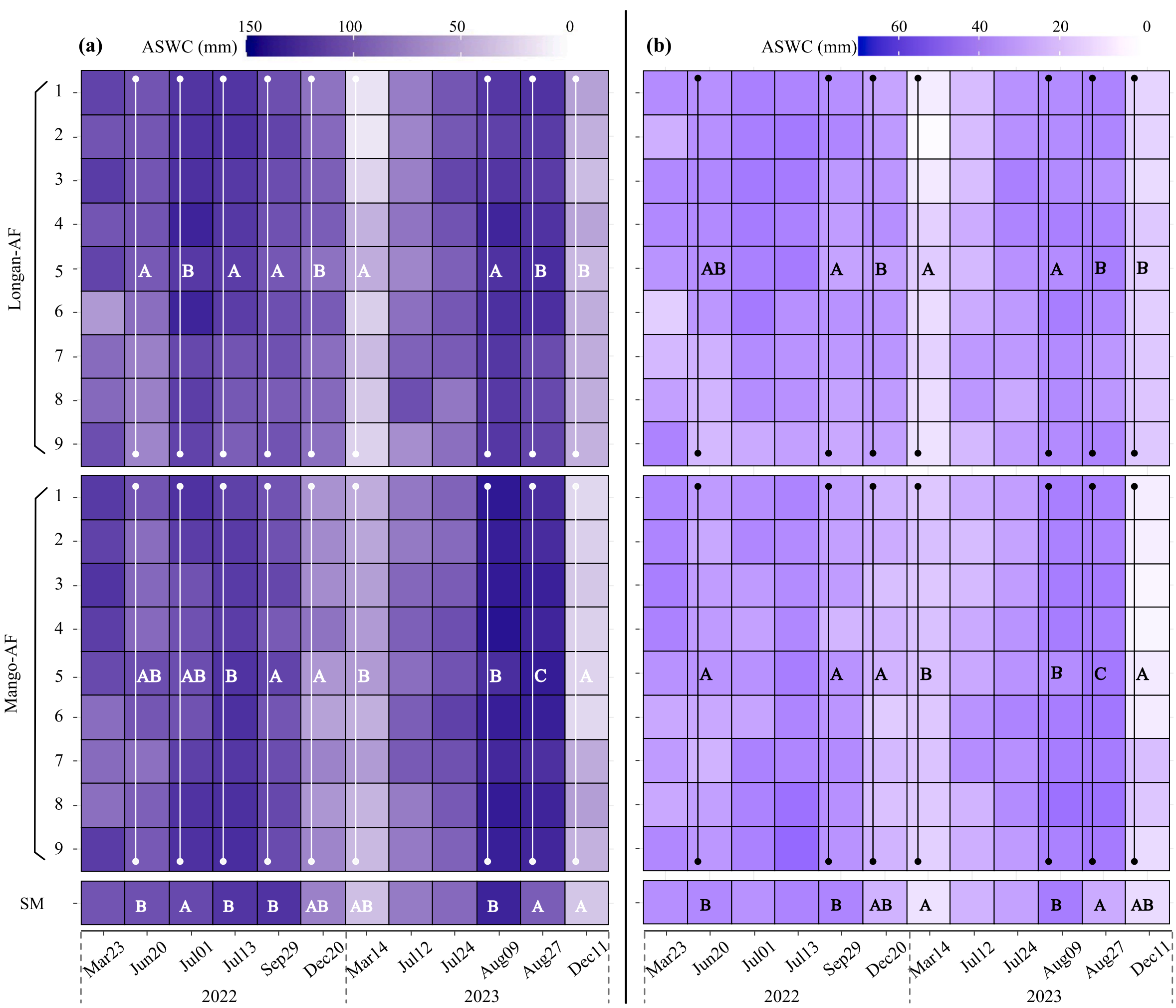

Fig. 5. Available soil water content (ASWC, mm) to 60 cm depth (**a**) and in 20–40 cm layer (**b**) in longan-maize-agroforestry (longan-AF), mango-maize-agroforestry (mango-AF), and sole-maize (SM) (sub-)treatments in 2022 and 2023. The letters indicate a significant difference between (sub-) treatments within each measurement occasion ($p \leq 0.05$, A < B).

3. Results

3.1. Distribution of available soil water in fruit-maize-grass agroforestry

3.1.1. Volumetric available soil water content

The ASWC down to 60 cm depth varied from 14 mm at the end of the dry season to a maximum of 141 mm during the growing season (July 2023). In the maize season, ASWC was higher in AF than sole-maize shortly after rainfall, whilst the opposite was the case when the measurement was taken several days after rainfall (p-value ranged, Fig. 5ab). During the early part of the dry season (i.e. in December 2022) the longan-AF had more ASWC (88 mm) than mango-AF (66 mm) and sole-maize (72 mm). However, towards the end of the dry season (i.e. in March 2023), the mango-AF had the highest ASWC (50 mm), followed by sole-maize (36 mm), and the longan-AF had the lowest (30 mm) (Fig. 5a).

After rain events, ASWC was generally lower below the tree and grass strip than in the upslope zones, although the difference was only significant on one occasion ($p < 0.001$) (Table S10). During the dry season, there was a tendency that zones upslope to the fruit trees (zones 3–5) had a higher average ASWC than downslope zones, except zones 3–5 in the mango-AF in December 2023 (Fig. 5a).

The ASWC in the 0–20 cm topsoil had a similar pattern to the whole 0–60 cm soil depth (Fig. S2a, Table S11). In the deeper soil layers (20–40 cm and 40–60 cm depths), there were similar distributions of spatial and temporal ASWC, but with smaller fluctuations compared to the topsoil. Nevertheless, the effect of different AF sub-treatments on ASWC during the dry seasons (in December and March) was more frequently significant in the 20–40 cm (Fig. 5b–Table S12) and in the 40–60 cm soil layers (Fig. S2b, Table S13) than in the topsoil. Moreover, ASWC in the longan-AF was lower in the topsoil layer than in the subsoil, contrasting to the mango-AF where it was higher in the topsoil than in the subsoil (Fig. S2a–b).

3.1.2. Dynamics of available soil water by sensors

The data from the single sensors in each measured zone and soil layer supported the patterns of ASWC derived by the gravimetric method (Fig. S2A). The ASWC in the topsoil layers in both longan-AF and mango-AF increased dramatically upon rain events and then decreased again but this was not as rapid as the prior increase (Fig. 6). The ASWC as determined by the sensors fluctuated more in the topsoil than in the subsoil.

3.2. Soil water infiltration

The average saturated infiltration rate was higher in the AF plot (~65 mm h^{-1}) than in the sole-maize plot (~11 mm h^{-1}) of the investigated replicate (Fig. 7). Within the AF plot, the highest average infiltration rate of about 100 mm h^{-1} was observed in the mango and longan rows (zone 5). The lowest infiltration rate of about 20 mm h^{-1}, was found above the mango and longan tree rows, but the results indicate large variation.

3.3. Maize yield, biomass, and harvest index

3.3.1. Grain yield

The average maize grain yield was higher in 2023 than in 2022 (3.8 and 2.4 ton ha^{-1}, respectively, $p < 0.001$). Sole-maize had a significantly higher yield per unit area of maize than the two AF sub-treatments ($p = 0.001$) in 2023, but not in 2022, causing a significant interaction. The maize yielded less in zone 7 (average 1.0 ton ha^{-1}) than in all other maize zones (average 3.2 ton ha^{-1}) in both AF sub-treatments across 2022–2023 (Fig. 8). Maize performed similarly in longan-AF and mango-AF.

3.3.2. Biomass

There was no significant difference in maize biomass between the

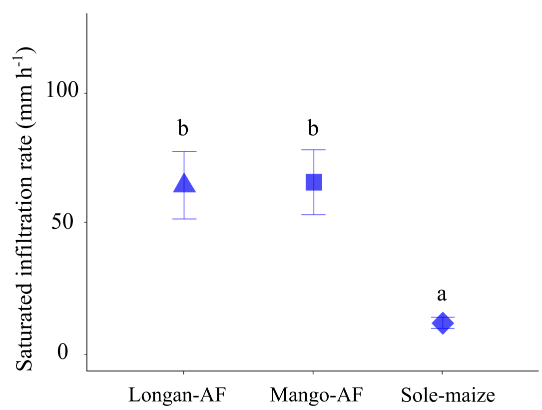

Fig. 7. Saturated infiltration rate in fruit (longan, mango)-maize-grass agroforestry plot (longan-AF, mango-AF) and a comparison with sole-maize plot in block 4, shown as mean ± standard error (bars). Different letters indicate significant differences at statistical level of $p = 0.05$, a<b.

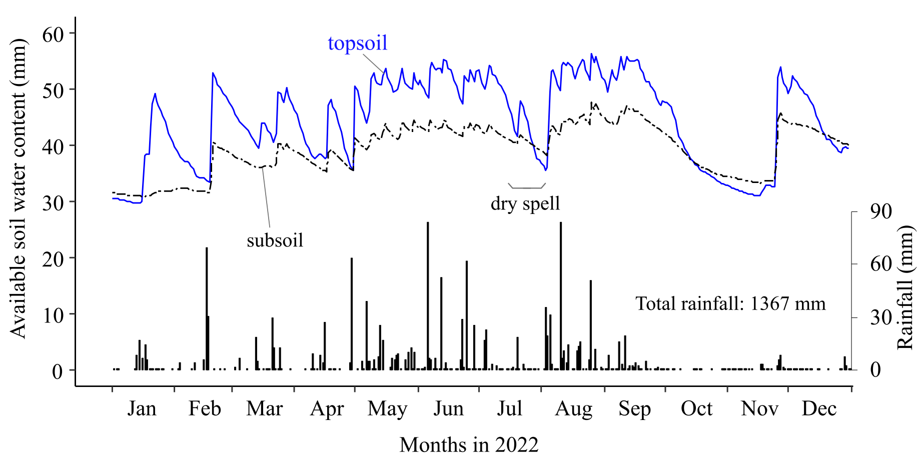

Fig. 6. The dynamics of ASWC (lines) in the topsoil layers (0–20 cm) as the average of the sensors at 10 cm depth in zones 4, 5, 6, and 7; and the subsoil (20–40 cm) in agroforestry (AF) as the average of the sensors at 30 cm depth in zone 5 of the longan-AF and mango-AF sub-treatments; and daily rainfall (bars), in 2022. There was only one sensor in each measured zone/soil layer; hence they were only used to follow the overall fluctuations over time.

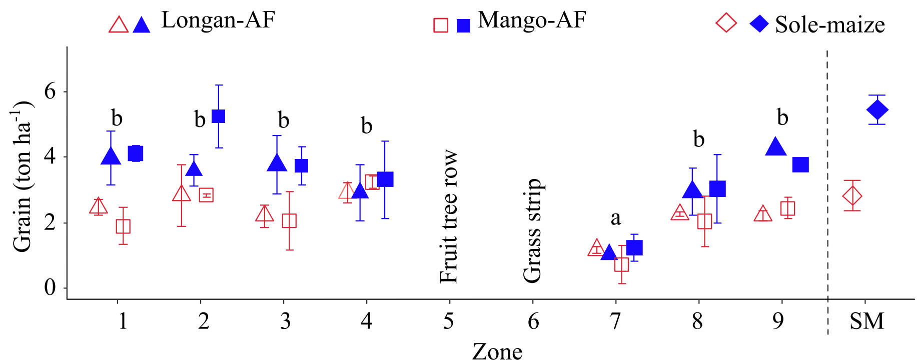

Fig. 8. Maize grain yield in different zones of longan-AF (triangles) and mango-AF (squares), and in sole-maize (SM) (diamonds) (sub)systems in 2022 (open red symbols) and 2023 (filled blue symbols). Data are means ± standard error (bars). The lettering indicates significant differences between zones in the agroforestry (sub)treatments ($p = 0.05$, a<b).

two seasons ($p = 0.96$), or between the two AF-sub-systems and sole maize across the seasons ($p = 0.13$). Similar to the grain yield, zone 7 had the lowest maize biomass (average 2.7 ton ha^{-1}) than other zones (average 7.2 ton ha^{-1}) in both AF sub-treatments (Fig. S3). The crop biomass increased with increasing distance from the tree rows on the downslope side, but it did not differ between the upslope zones.

3.3.3. Harvest index

The maize Harvest Index in 2023 (0.54) was higher than in 2022 (0.32) ($p < 0.001$) (Fig. 9). There was no significant difference between longan-AF, mango-AF, and sole-maize (sub-)treatments across seasons or within each season. Contrastingly to the results of maize grain yield and biomass, the HI was also not significantly different between zones in different slope positions within a particular year.

4. Discussion

4.1. Fruit trees and grass strips enhance water available for plant growth in agroforestry

4.1.1. Higher available water in agroforestry during and shortly after rain events

The ASWC fluctuated differently in longan-AF, mango-AF, and sole-maize (sub-)systems in both the rainy season (maize season) and the dry season. The higher average ASWC in agroforestry compared to sole-maize following rain events supports our first hypothesis regarding the AF system enhancing ASWC for plant growth. The higher ASWC was likely caused by enhanced water infiltration, as indicated by the measurements taken in one replicate of this study. Carbon-rich topsoil that had accumulated above the grass strips and formed terraces in the AF system [12], combined with the effect of the trees' root systems [52], and the soil cover from trees/grass [26,53] may have improved soil aggregation and decreased bulk density [43,54], leading to enhanced water infiltration and ASWC along the tree rows and grass strips [55]. Grass strips are also known to act as living fences that break the runoff and reduce the water flow out of the system [52]. Tuan et al. [13] conducted experiments in a similar environment, and reported guinea grass strips on sloping land reduced annual runoff volume by up to 61 %. Furthermore, Melville & Morgan [5] reported that small ponded areas were generated above contour-planted-grass strips on 5° slope in the UK, thereby allowing more time for water to infiltrate.

4.1.2. Soil water was taken up faster in agroforestry

The ASWC was lower in the AF system than in sole-maize when measurements were taken several days after rainfall, which suggests higher water use in the AF than in sole-maize. Thus, water was kept and utilised for production as opposed to being lost through runoff to lower land or streams. The large and stable leaf area of the AF systems [34–36], leading to high transpiration from trees and grass, is likely to use up water more rapidly in the AF system than in sole-maize. The ASWC was particularly low within and below the grass strips, corroborating earlier findings about high water consumption by grasses. The growth of the grass was highest during the rainy season, suggesting that the grass consumed a large quantity of water during this period. Indeed, Padovan et al. [57] reported that transpiration of an AF system reached 83 % of the potential evapotranspiration and was higher than that from a sole-coffee system (69 %). The importance of the cropping system for ASWC seemed more important in the dry season than in the rainy season. During the dry season, the ASWC in sole-maize was intermediate to that of the two AF sub-treatments, indicating large effect of fruit tree

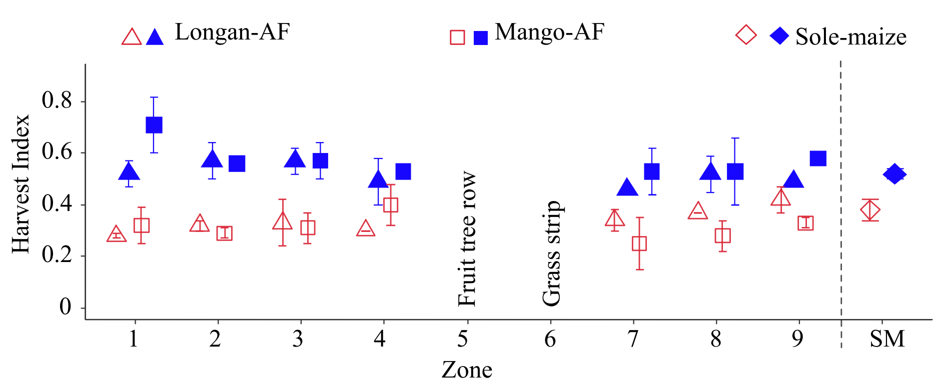

Fig. 9. Harvest Index of maize in different zones in longan-AF (triangles), mango-AF (squares), and sole-maize (SM) (diamonds) (sub)systems in 2022 (open red symbol) and 2023 (filled blue symbol). Data was visualised as mean ± standard error (bars). There was no significant difference when considering effect of zones, or effect of interaction between treatment and zone ($p > 0.05$).

species used in AF (see 4.3).

4.2. Slope position affects available soil water and maize yield

4.2.1. Soil water distribution in sloping agroforestry

The ASWC in the rainy season was typically higher in maize zones upslope than downslope of the tree rows and grass strips, indicating enhanced infiltration above the grass strips. This finding supports our second hypothesis which stated that ASWC would be greater in nearby upslope zones of the tree rows than downslope. This difference may be caused by the water retention effectiveness of grass strips that formed terraces, reduced the slope gradient, trapped runoff, and erosion, as discussed previously. The ample rainfall during the growing season could exceed tree/crop water requirement and lessen the effect of slope positions which could also explain the small and often not significant differences between zones in ASWC. During the dry season, the zone immediately upslope to the tree rows showed the same tendency during the rainy season, which was to have a higher average ASWC than other zones. This occurred despite the absence of intense rainfalls that could cause runoff and could instead be explained by greater shade from the fruit trees that reduced heat flux to the soil surface [25]. This was aided by longan and mango being evergreen fruit tree species [58,59] that maintain a stable vegetative soil cover through their canopy over seasons. Another explanation would be less grass competition in the upslope maize zone, therefore supporting higher ASWC compared to the zone downslope close to the grass strip.

4.2.2. Maize yield and biomass in relation to soil water distribution

The maize below the tree and grass strips (zone 7) yielded less grain and biomass than all other maize zones in 2022 and 2023, and this aligned with our expectation that maize yield and biomass would have a similar pattern to the ASWC distribution. The reduced yield of the maize that was closest to below the tree and grass rows is supported by studies on flat land in different regions, which reported a negative effect of different trees on maize close to the tree rows. However, the maize closest to above the tree rows did not follow this pattern. Although our previous study found lower incident light upslope and close to the tree row [25], the similar yield of upslope maize confirmed the potentially positive effect of the upslope position. Thus, it is unlikely that light was the most limiting factor, and crops could instead benefit from higher ASWC, as presented in this study, or by nutrient accumulation, as reported by Do et al. [12,22].

4.2.3. Effect of the dry spell in July 2022 on maize

The lower HI found in 2022, compared to 2023, was caused by a lower grain yield despite similar maize biomass. The low HI could be due to the water stress that occurred during a dry spell in July 2022 when maize was in the tasselling and silking stages (Fig. 4b). Stress during this period would have delayed silking, subsequently reducing the pollination effectiveness [64] and, therefore, the number of grains per cob and grain weight [65]. This demonstrates that even if total precipitation is sufficient, the rainfall distribution within the growing season can have a larger impact on yield. The HI within each year was similar in all maize zones indicating that differences in stresses between zones occurred in the juvenile stages of maize development and therefore affected biomass and grain yield equally [66]. The total amount of rainfall in our study site exceeded 800 mm during the crop seasons (Fig. 4b), whilst the water demand for similar yielding maize crops ranged from 400 to 600 mm in a study by Chen et al. [67]. This suggests that factors such as soil nutrients could be more important constraints to maize growth and yield than water in the AF system at this site.

4.3. Tree species have a larger effect on soil water during the dry season

By the end of the dry season (in March), ASWC in mango-AF was higher than that in longan-AF and this supports the third hypothesis which proposed that mango would compete less for water and improve ASWC during the dry season compared to longan. However, in the beginning of the dry season (in December) longan-AF had higher ASWC than mango-AF. The ASWC in the sole-maize treatment was intermediate to the two AF sub-systems during the dry season which indicates that tree species is a significant factor for ASWC. Indeed, the differences in growth habits and phenology between the two fruit tree species may have implications for competition and management. Longan flowered from February to April, whereas mango flowered earlier, from December to February, which is similar to previous reports for longan [18,20] and mango [15,16]. Fruit trees consume more water during the flowering stage than in any other stage [68], because of higher water demand for the expansion of plant cells and transportation of nutrients [69]. Longan trees have a more shallow root system than mango trees [37] and they therefore likely consumed more water in the shallow soil layers, whilst the mango trees likely took up more water from deeper soil layers due to their deeper roots. Thus, mango seems to have competed less for water in the shallow layers than longan. However, the lower ASWC in mango-AF during the mango flowering stage indicated that it also consumed water in the shallow soil layers. This may have been accentuated by the shallow soil profile which could not offer large water stocks at depth.

4.4. Agroforestry redesign and management strategy to optimise water resource on sloping land

4.4.1. The need of agroforestry design and management strategy

Management of potential competition plays a key role in the design of AF systems on sloping land, to achieve productivity and sustainability. In this study, water competition did not seem to be of major importance in the maize growing season except for the strong effect of the dry spell in July 2022. In a previous study, we found that there was an underutilisation of light resources, particularly during the dry season, and suggested an additional crop to optimise this resource [25]. However, there can be intense competition for water in the dry season, as indicated in the present study. To minimise the potential water competition from grass, farmers could cut grass earlier than current practices, particularly before sensitive maize growth stages [62]. Moreover, changing guinea grass, which was used in the current experiment, to a deeper-root grass, e.g. vetiver [70,71], would decrease resource demand in the shallow soil layers, where most of the annual crop root occurs. Selecting fruit tree species with deep root systems or practicing deep-planting [72] and root pruning [73] could enhance tree root distribution in deeper soil layers, thus reducing tree water consumption in the topsoil [74] and competition with grass, as previously discussed. Practicing appropriate fruit tree pruning would also help manage water demand and root development and competition [75,76].

4.4.2. Optimise soil water during rainy season for use in dry season

The primary water issues in this study site were high rain intensity during the rainy season which caused erosion and nutrient losses [12], and the lack of rain during the long dry season (Fig. 4a) to both sustain the fruit trees and enable planting of a dry season crop, e.g. as relay crop. Additionally, on sloping land with poor infrastructure, farmers have limited access to irrigation. The AF design and management plan should consider the possibilities of storing water in the rainy season for use in the dry season to benefit the fruit trees and dry season crops. Soil is the natural and the cheapest reservoir of water. To increase soil water, the input of water must be increased by reducing runoff and improving infiltration. Residue mulching or vegetative covering would support this [56]. Moreover, raising the organic matter content in the soil through manure/organic fertiliser application can improve infiltration capacity and water-holding capacity, and hence the ASWC [77]. Building artificial water storage is also a potential option for farmers. We observed that farmers in the region practice rainwater harvesting for different purposes (e.g. spraying fertilisers or plant protection compounds) by digging retention structures and using a canvas to build water tanks. Furthermore, farmers' groups in comparable regions have built rainwater-harvesting systems to collect runoff flow [78], even if it requires investment and consent from farmers because land is often fragmented with several farmers on the same slope. In addition, the significant differences we found between the impact of mango and longan on ASWC during different time periods and soil depths demonstrates the importance of choosing tree and crop species with different water requirements at their sensitive growth stages.

5. Conclusions

We conclude that fruit trees and grass strips increased ASWC up to 28 mm compared to sole-maize during and shortly after the rain events but also the water consumption between events. The ASWC tended to be higher upslope than downslope of tree rows and grass strips, whilst the difference was only significant on one occasion during the maize growing season. Maize below fruit tree rows and grass strips yielded 63 % less grain and 56 % less biomass than zones both immediately upslope and midway between tree rows. However, the harvest index was similar in all slope positions in the AF and in the sole-maize system, indicating that the difference between positions regarding competition occurred when maize was in juvenile stages and cannot be linked to water deficit. Mango reduced shallow ASWC 10 % less during the dry season than longan, but their effect on maize yields were similar in the experiment and no conclusions can be drawn regarding their competitive ability in the rainy season.

We also conclude that ASWC was not the main limiting factor affecting crop performance during the rainy season even if a drought immediately before and during flowering in 2022 is likely to have affected yield. However, competition during the dry season could be an important factor for fruit tree yield, maize establishment, and the possible inclusion of a dry season crop.

Ensuring soil health through management of soils for high infiltration capacity is essential during the rainy season, and AF systems could possibly be further enhanced by rainwater harvesting for storing and irrigating in the dry season, which would optimise the use of soil water resources. Fruit tree/crop phenology and morphology should be considered when redesigning and planning management for sloping agroforestry systems.

CRediT authorship contribution statement

Huu Thuong Pham: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jennie Barron:** Writing – review & editing, Methodology. **Göran Bergkvist:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Ingrid Öborn:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Nguyen La:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Rachmat Mulia:** Writing – review & editing, Supervision, Funding acquisition. **Sigrun Dahlin:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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