Carbon stock potential of Indonesian local fruit trees, some collections of Purwodadi Botanic Garden

T Yulistyarini* and J T Hadiah

Research Centre for Plant Conservation and Botanic Gardens, National Research and Innovation Agency, Jl. Ir. Juanda 13 Bogor, West Java Indonesia

*Corresponding author e-mail: tyulistyarini@yahoo.com

Abstract. Restoration programs improve the quality of degraded ecosystem and play a role in mitigating climate change. Selection of plant species based on carbon sinks has been widely used in such programs, including using fruit trees. The purpose of this study was to estimate the carbon stock of several local fruit species collections at Purwodadi Botanic Garden in order to determine their potential as carbon storage. Above ground C stock estimation was conducted using a non-destructive method by measuring stem diameter at breast height (DBH) and tree height. The age of sampled fruit trees ranged between 20–60 years. Biomass was obtained by calculating using allometric equation. The results showed that sixty years old Diospyros malabarica (Desr.) Kostel. stored the highest carbon (163 Mg C.ha⁻¹). Whereas, the lowest carbon stock was stored by forty years old Stelechocarpus burahol (Blume) Hook.f. & Thomson (1.4 C tonnes.ha⁻¹). Findings of this study suggested that most observed local fruit trees are potential carbon sinks and must be promoted in restoration programs to help mitigate climate change. Diospyros malabarica (Desr.) Kostel, Flacourtia rukam Zoll. & Moritzi, Garcinia dulcis (Roxb.) Kurz., Protium javanicum Burm.f, Sandoricum koetjape (Burm.f.) Merr., and Syzygium cumini (L.) Skeels were recommended as priority species for restoration.

Keywords: carbon stock, biomass, fruit trees, restoration.

1. Introduction
Restoration is an effort to renew, recover and improve degraded and damaged ecosystems and habitats. Vegetation restoration significantly influences soil characteristics in croplands and restored areas [1]. It also has an effect on understory species composition by modifying understory environments [2]. In South China, restoration of a monoculture Eucalyptus plantation using enriched planting of native tree species significantly lower surface water flow and soil erosion [3]. Ecosystem restoration also plays a role in mitigating climate change, which is to significantly increase carbon uptake. [4] reported that second-growth forests in the Amazon were able to accumulate a total aboveground carbon stock of 8.48 Pg C ha⁻¹ year⁻¹ through low-cost natural regeneration.

The Indonesian government has made efforts to reforest degraded lands. The 2020-2024 Strategic Plan of the Ministry of Environment and Forestry stated that the direction of forest management has been changed from initially focusing on timber management towards forest resource ecosystem and community-based management. Restoration programs can be developed in the form of sustainable agroforestry systems with various types of multi-stratified plants based on local knowledge to increase the chances of success due to acceptance by the local community [5]. Such programs have widely used selected plants based on carbon sinks including fruit trees.
Fruit plant species are multipurpose trees, often planted in home gardens and agroforestry systems. The two systems have great potentiality for carbon sequestration. [6] reported that mango (Mangifera spp.) and jackfruit (Artocarpus heterophyllus) were dominant species planted at home gardens in Bangladesh, and contributed to the carbon stock of this cropping system. [7] quantified C stock of fruit-based rubber agroforestry in Central Kalimantan with >100 years of age, and stated that this agroforestry system stored carbon up to 415 Mg ha\(^{-1}\). Several fruit tree species with high importance values, such as Baccaurea spp., durian (Durio zibethinus L.), rambutan (Nephelium lappaceum L.) and Syzygium lineatum (DC.) Merr. & L.M.Perry, were potential carbon sinks. [8] reported that Durio zibethinus L., Lansium domesticum Corrêa, Mangifera indica L., and Nephelium lappaceum L. were planted as shade trees at cacao agroforestry in South Sulawesi because of their long-term economic values.

Indonesia is one of the centers for tropical fruit diversity. However, many Indonesian species of fruit trees have low commercial values such as rukam (Flacourtia rukam), jamblang (Syzygium cumini) and buni (Antidesma bunius). Such low commercially valued fruit trees are categorized as underutilized fruit trees (UFTs). UFTs are less known particularly to people aged 21-40 years old and started to disappear from local and regional markets [9]. The development of such fruit plants is required to conserve the species, such as revealing the ecological potential. Restoration programs require many local trees because plant diversity affects ecosystem function [10]. Therefore, it is necessary to explore the potential of plant species in providing ecosystem services such as carbon sequestration capabilities. The purpose of this study was to estimate the carbon stock of several local fruit species collections at Purwodadi Botanic Garden to determine their carbon storage potential.

2. Study Site and Methods
This study was conducted in February–March 2021 at Purwodadi Botanic Garden (PBG) in Pasuruan East Java. The study site is located at an altitude of 300 meter above sea level, with an average annual rainfall of 2283 mm, average humidity 78%, and temperature 19–34°C [Registration Unit PBG, unpublished]. PBG collections of local fruit trees observed in this study comprised 18 species (Table 1), all of which are from the Indo-Malesia geographic range. The age of sampled fruit trees ranged between 20–60 years, with 2–5 replications for each species. The estimation of individual tree aboveground biomass (AGB\(_{\text{est}}\)) was conducted using a non-destructive method by measuring stem diameter at breast height (DBH) and tree height. The tree biomass was estimated by calculating using allometric equation biomass in humid habitat as follows:

\[
(\text{AGB})_{\text{est}} = 0.0509 \times \rho D^2H \quad [11]
\]

Where \(\rho\) is wood density (g.cm\(^{-3}\)) [12], \(D\) is DBH (cm), \(H\) is tree height (m)

Carbon stock was estimated by multiplying the biomass with allometric values for carbon stock i.e. 0.46 [11]. Carbon stock per hectare is the total C stock of each species when planted in spacing for fruit trees in general, i.e. 8 m x 8 m.
**Table 1.** List of fruit tree species observed in this study.

| No | Species                     | Family          | Local name | Age (years) | Natural habitat                                                                 | Type                  | Other uses                                |
|----|-----------------------------|-----------------|------------|-------------|---------------------------------------------------------------------------------|-----------------------|-------------------------------------------|
| 1  | *Aegle marmelos* (L.) Correa | Rutaceae        | Maja, Bel fruit | 50          | up to 500 m asl, on swampy land and dry soils                                    | deciduous, small-medium tree | medicine, dye                            |
| 2  | *Antidesma bunius* (L.) Spreng. | Phyllanthaceae | Buni       | 40          | up to 1800 m asl, lowland to to montane rain forest, part. shade up to 500 m asl | evergreen, medium tree | timber                                    |
| 3  | *Artocarpus integer* (Thunb.) Merr. | Moraceae | Chempedak | 60          | up to 500 m asl, often on wet hillsides, evergreen, medium tree                  | timber, bark to make rope, |                                           |
| 4  | *Averrhoa bilimbi* L. | Oxalidaceae | Belimbing asam | 20          | up to 500 m asl                                                                  | evergreen, small tree  | medicine                                  |
| 5  | *Baccaurea dulcis* (Jack) Müll.Arg | Phyllanthaceae | Cupa      | 40          | at 90–700 m asl, at 90–700 m asl, tropical lowland forest                       | evergreen, dense medium-large tree | timber, medicine, ornamental and shade trees |
| 6  | *Bouea macrophylla* Griff. | Anacardiaceae | Gandaria, Plum mango | 40          | up to 300 m asl, lowland forest                                                  | evergreen, dense, medium-large tree | timber, shade trees                       |
| 7  | *Cynometra cauliflora* L. | Fabaceae        | Nam nam, kopi anjing | 20          | wet tropical lowland                                                            | evergreen, small tree  | ornamental plant                          |
| 8  | *Diospyros discolor* Willd. | Ebenaceae       | Buah mentega, Bisbul | 30          | 0–800 m asl, almost any soil                                                     | evergreen, large tree   | the wood for making handicrafts           |
| 9  | *Diospyros macrophylla* Blume | Ebenaceae       |            | 30          | up to 800 m asl, clay, sandy and rocky soil                                     | evergreen, medium to large tree | timber                                    |
| 10 | *Diospyros malabarica* (Desr.) Kostel | Ebenaceae | River eboni | 60          | up to 500 m asl, the moist lowland forest                                        | evergreen, large tree   | medicine, timber                          |
| 11 | *Flacourtia rukam* Zoll. & Moritzi | Salicaceae | Rukem      | 40          | up to 1500 m asl                                                                | evergreen, small tree  | bark for dye mats; seed to cure swelling  |
| 12 | *Garcinia dulcis* (Roxb.) Kurz | Clusiaceae      | Mundu      | 60          | humid tropic in SE Asia                                                        | evergreen, medium tree  | medicine, timber, rootstock              |
| 13 | *Limonia acidissima* L. | Rutaceae        | Kawista    | 50          | up to 450 m asl, moonsoon to dry climate                                          | deciduous, small tree  | bark and spines for medicine; timber     |
| 14 | *Manilkara kauki* (L.) Dubard | Sapotaceae      | Sawo kecik | 40          | < 500 m asl, coastal regions, dry climates                                        | evergreen, medium tree  | medicine, rootstock                      |
| 15 | *Protium javanicum* Burm.f. | Burseraceae     | Tenggulun  | 30          | up to 800 m asl                                                                | evergreen, medium to large tree | a cover crop in teak plantations          |
Table 1. List of fruit tree species observed in this study (continued).

| No | Species | Family | Local name | Age (years) | Natural habitat | Type | Other uses |
|----|---------|--------|------------|-------------|----------------|------|------------|
| 16. | *Sandoricum koetjape* (Burm.f.) Merr. [15] | Meliaceae | Kecapi, Santol | 30 | 0–800 m asl, lowland dipterocarp forest | deciduous, small to large tree | timber, erosion control, bark for tanning, shelter, medicine |
| 17. | *Stelechocarpus barahol* (Blume) Hook.f. & Thomson [13,18] | Annonaceae | Kepel | 40 | up to 600 m asl., deep moist clay soil | evergreen, large tree | anti-oxidant |
| 18. | *Syzygium cumini* (L.) Skeels. [15] | Myrtaceae | Juwet, Jamblang | 60 | up to 600 m asl, with over 1000 mm annual rainfall | evergreen, large tree | shelter coffee tree |

3. Results and Discussion

3.1. Carbon stock in local fruit tree species

Table 2 showed the estimated C stock of fruit tree species collections of PBG at various ages. The eighteen local fruit tree species indicated significant contributions to carbon sequestration based on age and growth size. The sixty years old *Diospyros malabarica* stored the highest biomass (2267.8 kg) and contributed total C stock of 1043.2 kg C plants\(^{-1}\) or 163 Mg C ha\(^{-1}\). The carbon storage of the plant showed the highest among other species observed particularly those of the same age. The fifty years old *Aegle marmelos* had larger C stock than the fifty years old *Limonia acidissima* (both Rutaceae). Whereas *Flacourtia rukam* stored the highest C stock amongst the forty years old trees, and *Stelechocarpus barahol* stored the lowest. The thirty years old group comprised four species namely *Diospyros discolor*, *Diospyros macrophylla*, *Protium javanicum* and *Sandoricum koetjape*. *Protium javanicum* stored the highest C stock of 86 Mg C ha\(^{-1}\) in the group, while *Diospyros macrophylla* stored the lowest C stock of 5 Mg C ha\(^{-1}\). Within the twenty years old group, *Cynometra cauliflora* had larger C stock than *Averrhoa bilimbi* (45.1 Mg C ha\(^{-1}\) and 6.1 Mg C ha\(^{-1}\), respectively). This study also showed that species within the same age group may have different DBH and carbon stock. The amount of carbon stock in tree biomass is correlated to tree growth and development that are influenced by abiotic factors such as nutrients, light, water, and stress tolerance [19].

Carbon stock value relates to the species growth characteristics i.e. fast- or slow-growing which is evolutionary controlled by gene [20]. In the 60 years old group, *Diospyros malabarica* which is categorized as a large tree (Table 1) possessed the highest DBH among all plants observed (Table 2). *Syzygium cumini* is also a large tree, but this species produced less biomass than *Diospyros malabarica*. The former has a higher wood density (WD=0.76 g cm\(^{-3}\)) than the latter (WD=0.72 g cm\(^{-3}\)) so that the growth of the former is slower than that of the latter. Species with high wood density is categorized as a slow-growing species. On this type of plant, carbon accumulation occurs more slowly in the long-term. Whereas fast-growing species usually has low wood density such as *Artocarpus integer* (WD=0.56 g cm\(^{-3}\)) which accumulates large amounts of carbon in the first stage of their lifespan [10]. However, further research on the growth properties is needed to confirm this hypothesis by studying the growth rate of each species.

In the 50 years old group, *Aegle marmelos* and *Limonia acidissima* are small-medium tree with high wood density (0.771 g cm\(^{-3}\) and 0.84 g cm\(^{-3}\), respectively). Tree biomass is strongly influenced by wood density. The value of wood density is very influential in calculating the estimated dry weight of tree biomass. The higher the wood density value, the greater the dry weight value of tree biomass and the higher the carbon stored in the tree [21]. Most of the species in the 40 years old group are medium-sized trees, except *Stelechocarpus barahol* which is a large tree. Nevertheless, this species showed the lowest biomass in the group. The plant had stunted growth due to unfavorable environmental factors such as too shaded habitat.
Table 2. Biomass and C stock estimation of eighteen fruit tree species in PBG at various ages.

| No. | Species                          | Age (years) | Wood density (g.cm⁻¹) | DBH (cm) | Biomass (kg.plant⁻¹) | C stock (kg.plant⁻¹) | C stock (Mg.ha⁻¹) |
|-----|---------------------------------|-------------|------------------------|----------|----------------------|---------------------|-------------------|
| 1   | Cynometra cauliflora L.         | 20          | 0.72                   | 29.44    | 288.5                | 132.7               | 43.1              |
| 2   | Averrhoa bilimbi L.             | 20          | 0.52                   | 21.34    | 84.4                 | 38.8                | 6.1               |
| 3   | Protium javanicum Burn.f.      | 30          | 0.75                   | 41.72    | 1196.0               | 550.2               | 86.0              |
| 4   | Sandoricum koetjape (Burm.f.) Merr. | 30        | 0.56                   | 47.45    | 1091.1               | 501.9               | 78.4              |
| 5   | Diospyros discolor Willd.      | 30          | 0.88                   | 24.84    | 593.2                | 272.9               | 42.6              |
| 6   | Diospyros macrophylla Blume    | 30          | 0.48                   | 14.61    | 70.0                 | 32.2                | 5.0               |
| 7   | Flacourtia rukam Zoll. & Moritzi | 40       | 0.75                   | 30.94    | 744.2                | 342.3               | 53.5              |
| 8   | Antidesma bunius (L.) Spreng   | 40          | 0.51                   | 39.64    | 527.7                | 242.7               | 37.9              |
| 9   | Manilkara kauki (L.) Dubard    | 40          | 0.83                   | 22.74    | 263.6                | 121.3               | 18.9              |
| 10  | Bouea macrophylla Griff.       | 40          | 0.69                   | 22.71    | 181.1                | 83.3                | 13.0              |
| 11  | Baccaurea dulcis(Jack) Müll.Arg | 40       | 0.49                   | 21.97    | 118.5                | 54.5                | 8.5               |
| 12  | Stielechocarpus burahol (Blume) Hook.f. & Thomson | 40 | 0.55 | 10.83 | 19.7 | 9.1 | 1.4 |
| 13  | Aegle marmelos (L.) Correa    | 50          | 0.771                  | 24.76    | 374.8                | 172.4               | 26.9              |
| 14  | Limonia acidissima L.          | 50          | 0.84                   | 21.84    | 1864.4               | 85.7                | 13.4              |
| 15  | Diospyros malabarica (Desr.)Kostel | 60       | 0.72                   | 62.74    | 2267.8               | 1043.2              | 163.0             |
| 16  | Garcinia dulcis(Roxb.) Kurz    | 60          | 0.73                   | 51.75    | 784.1                | 360.7               | 56.4              |
| 17  | Syzygium cumini (L.) Skeels.   | 60          | 0.76                   | 40.87    | 672.7                | 309.5               | 48.4              |
| 18  | Artocarpus integer (Thunb.) Merr. | 60       | 0.56                   | 22.29    | 99.2                 | 45.6                | 7.1               |

Four tree species in the 30 years old group were all categorized as large trees. The plants in this group still have the ability to increase biomass and carbon, because they have not reached their maximum growth yet. Similarly, [20] mentioned that some Dillenia species indicated increasing biomass and carbon storage in the 20–30 years of age. She stated that the plants maximized the leaf and root growth in the first 10 years and the stem growth in the second to third 10 years by storing more carbon. In addition, [22] mentioned that carbon sequestration rates of ecological trees achieve their peaks 25–30 years after planting, and are steady after 50 years of age as the trees reached their maximum growth. [23] stated that old trees (50 years and above) have accumulated carbon for a long time and maintained high rates of carbon storage at later stages of their lifetimes.

The carbon stock of individual local fruit trees species observed in this study ranged from 1.4–163 Mg C.ha⁻¹. These values were lower than that of Dipterocarpaceae in Central Kalimantan (C stock of 928.86 Mg C.ha⁻¹) [24]. The 30 years old Sandoricum koetjape at PBG stored carbon of 78.4 Mg C.ha⁻¹. This values is similar to that of the 32 years old santol (Sandoricum koetjape) plantation in the Philippine i.e. 75.02 Mg C.ha⁻¹. Carbon storage of some local UFTsuch as Diospyros malabarica (163 Mg C.ha⁻¹), Flacourtia rukam (53.5 Mg C.ha⁻¹), Protium javanicum (86 Mg C.ha⁻¹), and Syzygium cumini (48.4 Mg C.ha⁻¹) was higher than that of high economic valued fruit trees such as mango and rambutan. The 15 year old mango plantation in the Philippine stored 45.29 Mg C.ha⁻¹, and the 12 year old rambutan plantation reserved 11.12 Mg C.ha⁻¹ [25]

3.2. Implications to restoration programs
Restoration proposes a potential solution for reversing biodiversity loss and promotes carbon sequestration in such degraded forests [26]. The purposes of restoration programs are not only to fulfill the daily necessities but also to restore ecosystem functions, such as wildlife habitat, water and nutrient cycling, temperature and humidity regulation, mitigations of flood and landslide. Some of the observed local fruit trees showed potential as high and long carbon stocks. From the result of C stock
estimation, species with the highest C stock in each age group are recommended as priority species for restoration programs namely *Diospyros malabarica*, *Flacourtia rukam*, *Garcinia dulcis*, *Protium javanicum*, *Sandoricum koetjape*, and *Syzygium cumini*.

Some other species can be added to the list of priority species for restoration programs particularly regarding their carbon sequestration potential, namely *Diospyros discolor*, *Sandoricum koetjape*, and *Syzygium cumini*. *Sandoricum koetjape* has a low WD of < 0.6 g cm\(^{-3}\), thus this species is a fast-growing plant that produces biomass faster. Meanwhile [27] reported that *Diospyros discolor* and *Syzygium cumini* are categorized as slow-growing plants and have high carbon stock in their seedling phase.

Planting local fruit species with high carbon stock potential as shade trees in agroforestry systems seems to be a starting point towards achieving ecosystem restoration. [8] stated that the higher tree density in cacao-based systems resulted in higher carbon stocks. They reported some fruit trees such as *Durio zibethinus*, *Lansium domesticum*, and *Nephelium lappaceum* which have medium to high WD (> 0.6 g cm\(^{-3}\)) in cacao agroforestry contributed to 30–40% of aboveground C stock. In terms of restoration, after C stocks enhancement is achieved, it is usually followed by an increase in diversity. High diversity is achieved as a result of natural seed dispersal [28]. Agroforestry systems intend to take an intermediate position between the degradation and restoration leg because this system supports a higher diversity [8].

The challenge faced today is that people preferred shade trees with long-term economic benefits such as timber and fruit trees of high economic value. Whereas the observed local fruit tree species which are under-utilized fruit trees, usually produce fruits that are sour or tasteless (Table 1), so they require processing prior to consumption. The fruits of these species are processed into pickles or jams. Therefore, better processing efforts are needed for the post-harvest of these species. In addition, other uses of these local fruit trees such as medicine, ornamental plant, erosion control, need to be developed.

Based on their natural habitat, most of the studied local fruit trees can be planted to restore degraded ecosystems in dry lowland habitats (<600 m asl). Some species such as *Antidesma bunius*, *Baccaurea dulcis*, *Diospyros discolor*, *Diospyros malabarica*, and *Flacourtia rukam* show a wider distribution from 0–1500 m asl (Table 1). Therefore these five species can be planted for restoration programs both in lowland and highland areas. Most of the observed local fruit trees are large, evergreen species, thus they are also suitable as shade trees in agroforestry such as cacao or coffee agroforestry. *Aegle marmelos* and *Limonia acidissima* are small, deciduous trees. Both belong to the citrus family (Rutaceae) and produce fruits that can be processed into syrup or jams.

The amount of carbon accumulation in woody biomass is very dependent on plantation age, stem density, site condition, climatic condition, and management practice [29]. In the field, tree planting in restoration programs does not always apply correct silviculture practices, with little or no soil preparations, nutrient applications, and weed controls. [30] proved that intensive silviculture in restoration increased growth and carbon sequestration. Intensive silviculture, especially during the early stages of plantation, supplies nutrients, controls weed competition, and enhances physical and biological site conditions.

4. Conclusion
Most of the observed local fruit trees are high carbon stock potential. *Diospyros malabarica* (Desr.) Kostel, *Flacourtia rukam* Zoll. & Moritzi, *Garcinia dulcis* (Roxb.) Kurz., *Protium javanicum* Burm.f. *Sandoricum koetjape* (Burm.f.) Merr., and *Syzygium cumini* (L.) Skeels were recommended as priority species for restoration programs.

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