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Short Communication: Investigating environmental impacts of long-term monoculture of sugarcane farming in Indonesia through DPSIR framework

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Abstract. *Putra RP, Ranomahera MRR, Rizaludin MS, Supriyanto R, Dewi VAK. 2020. Short Communication: Investigating the environmental impacts of long-term monoculture of sugarcane farming in Indonesia through DPSIR framework. Biodiversitas 21: 4945-4958.* An increasing trend of sugar demand in Indonesia due to the rising population has forced the government to boost its national sugarcane production through intensification program. Long-term monoculture system has long been practiced by sugarcane growers in Indonesia, particularly by large sugar companies for more than 30 years. This farming method bolsters the government's program in scaling-up national sugar production. Through a literature study, the present study analyzed the impacts of long-term sugarcane monoculture in Indonesia on agroecosystem functions by using the Driver-Pressure-State-Impact-Response (DPSIR) framework. Results showed that long-term sugarcane monoculture leads to decreased soil quality, lowered hydrological functions, reduced agrobiodiversity, and increased greenhouse gas emissions. Those conditions corresponded to reduced sugarcane yield and productivity, increased pests and diseases, decreased income gained by growers, higher dependencies on chemicals, and higher cultivation costs. In the end, we proposed several sustainable crop management to mitigate the detrimental effects of sugarcane monoculture practice in Indonesia. These include performing crop break or rotation with legume or the other cash crop, intercropping, green harvesting and trash blanket, precision agriculture methods, and soil amendment with organic matters. However, some constraints in implementing those sustainable crop management, such as inadequate knowledge and capital, should be considered. The information given in this study can be used by sugarcane growers or companies, policymakers, and sugarcane-related stakeholders as considerations to improve sugarcane productivity while at the same time minimizing its impact on the environment.

Keywords: DPSIR, environment, Indonesia, monoculture, sugarcane

INTRODUCTION

Sugarcane (*Saccharum officinarum* L.) is one of the essential estate crops in Indonesia, and it has an important role in the country's economy. The increased population and income per capita, as well as a change in diets among the people, leads to the increased demand for cane sugar in Indonesia over the past decades. However, it is not followed by a rise in domestic sugar production. The area of sugarcane plantations is declining over time (NSC 2020), which further hampering sugar production, and therefore increasing the gap between sugar consumption and production in the country (Solomon et al. 2016; Toharisman and Triantarti 2016; Sulaiman et al. 2019). The reduction of the sugarcane plantation area in Indonesia has been linked to several socio-economic factors, such as fluctuation in sugar price, high production costs, the absence of subsidized fertilizers, and farmers' preference to opt for the other crops that are more profitable over sugarcane. In response to such production issue, the Indonesian government, through its Ministry of Agriculture, had implemented an agriculture intensification program aimed to boost its national sugarcane production. The program, called "Tebu Rakyat Intensifikasi (TRI)", forces landowners to plant sugarcane in their land. This program was introduced in 1975 and ended in 1998.

In some areas of Indonesia, especially in Java and Sumatera Island, lands are converted into sugarcane plantations, in which the monoculture system has been by far a predominant farming practice applied by Indonesian sugarcane growers (Kusumawati et al. 2020). Monoculture refers to the cultivation of single crops within the given area at a time, and in this case, sugarcane is the only crop cultivated by the growers. Sugarcane growers in Indonesia tend to cultivate this crop without rotation systems, meaning that they continuously grow sugarcane throughout farming seasons. Farmers in Java Island, for instance, are encouraged by the Indonesian government to grow sugarcane over the other crops and expected not to shift it into other commodities. Although this farming method supports the government's intensification program, foregoing studies have revealed that long-term sugarcane monoculture leads to some ecological problems and reduced crop productivity. Large-scale sugarcane cultivation has been associated with land-use changes; thus, adversely impact the environment, such as causing soil degradation, water, and air pollution, as well as biodiversity loss (Hess et al. 2016; Hawkins 2018).

This study will help to contribute to a better understanding of environmental impacts caused by sugarcane monoculture by identifying possible long-term consequences of such a farming system toward several environmental indicators such as soil quality, hydrological function, agrobiodiversity, GHG emissions, fire risk, and their impacts on socio-economic aspects. This study emphasizes on the environmental side of the long-term sugarcane monoculture. It includes some options for sustainable cultivation management to help in mitigating the problem. The results of this study can be used by sugarcane-related stakeholders as a consideration to improve sugarcane productivity without sacrificing the environment.

MATERIALS AND METHODS

A Driving force-Pressure-State-Impact-Response (DPSIR) framework was used to generate a comprehensive view concerning possible environmental impacts caused by long-term monoculture cultivation of sugarcane in Indonesia. The DPSIR is a practical framework intended for assessing the impacts of anthropogenic activities on the environment and vice versa since the components within the framework are interdependent. The framework was firstly proposed by Rapport and Friend (1979), then it was adapted and widely introduced by the Organization of Economic and Development (OECD) as a tool for environmental reporting. The DPSIR framework was chosen because of its simplicity and its powerful communication tool linking the environment to society, and vice versa.

A DPSIR framework comprises the following components: driving forces, pressures, states, impacts, and responses (Maxim et al. 2009). Driving forces are the socio-economics or socio-economical facets of human activities determining the magnitude of environmental problems. Pressures are the exposure of ecosystems to the threats due to anthropogenic activities. States are measurements of the changes in environmental conditions. Impacts are the consequences caused by states on biodiversity and ecosystem functioning. Responses are regulatory and strategic actions that society can do to reduce the adverse effects of each of the four prefacing framework components (Hester and Harrison 2007).

RESULTS AND DISCUSSION

A DPSIR diagram has been drawn according to the literature search and the authors' professional experience related to sugarcane monoculture (Figure 1). Starting from the "Driving forces", the DPSIR diagram is basically a loop-line system that ends at the "Response". In the end, the response addresses the sub-criteria within the Driving forces, symbolized with an arrow. All arrows within the diagram denote the general cause-and-effect relations amongst the framework components. The arrows can be read as something 'leads to' or 'produces' the subsequent box. Double arrows indicate feedback loops.

Driving Forces (D) of long-term monoculture of sugarcane farming in Indonesia

Indonesia's demand for sugar is rising over time due to the growth of population which has attained 1.3% annually (Statistics Indonesia 2018; Sulaiman et al. 2019; NSC 2020) (Figure 2), increased income (Sulaiman et al. 2019), as well as growing demand from food and beverage industries (Toharisman and Triantarti 2016). The total world production for sugarcane accounts for up to 1.9 billion tons, while in Indonesia, it reaches up to 2.2 million tons (FAO 2018). Despite accounting only 0.12% of the total world production, the average growth rate of sugarcane consumption in Indonesia increased by up to 2% annually since 1996, and in 1997, the government initiated sugar import to the country (Pu 2015). To meet the national sugar demand in 2020, for instance, the country needs to import at least 1.5 million tons (NSC 2020). In Indonesia, sugar consumption is intended for both household and industrial uses (Toharisman and Triantarti 2016).

Consumers' dependency on cane sugar is also very high since there is a small tendency to substitute with synthetic sugar or the other artificial sweeteners. In Indonesia, artificial sweeteners have a very segmented market, namely only for diabetic people or persons in a diet program. Sugarcane is a primary sugar-producing raw material in the world, including Indonesia. Sugarcane accounts for 80% of the sugar produced in the world (Sharma and Chandra 2017). Most of the rest can be made either from sugar beets, palm sugar, stevia, or maize.

The other driving forces for sugarcane growers to implement a monoculture system in their field are the easiness or practicality of doing it and low production cost. In Indonesia, sugarcane is mostly grown for several years, while the whole above-ground biomass is harvested each year. Under-ground parts (roots) remain in the soil since they are expected to re-grow, and this process is called ratooning.

Pressures (P) of long-term monoculture of sugarcane farming in Indonesia

Due to increased sugar demand in Indonesia, the sugar production needs to be improved via intensifying the cultivation system. In addition to this, lands used for sugarcane cultivation also needs to be expanded (Djajadi 2015). As sugarcane belongs to the C4 plant, it is considered as one of the most efficient photo-synthesizers in the plant kingdom. This feature makes sugarcane can easily grow in tropical regions, such as Indonesia, given the fact that the country has plenty of sunlight throughout the year. Nevertheless, not all areas in Indonesia are suitable for sugarcane cultivation due to variations in soil characteristics as well as climate conditions (Sulaiman et al. 2019). Therefore, sugarcane cultivation in Indonesia is intensified in certain areas. In 2018, a total of 10 provinces had become the main sites of sugarcane cultivation in Indonesia, mostly located on Java Island due to its high soil fertility (Figure 3).

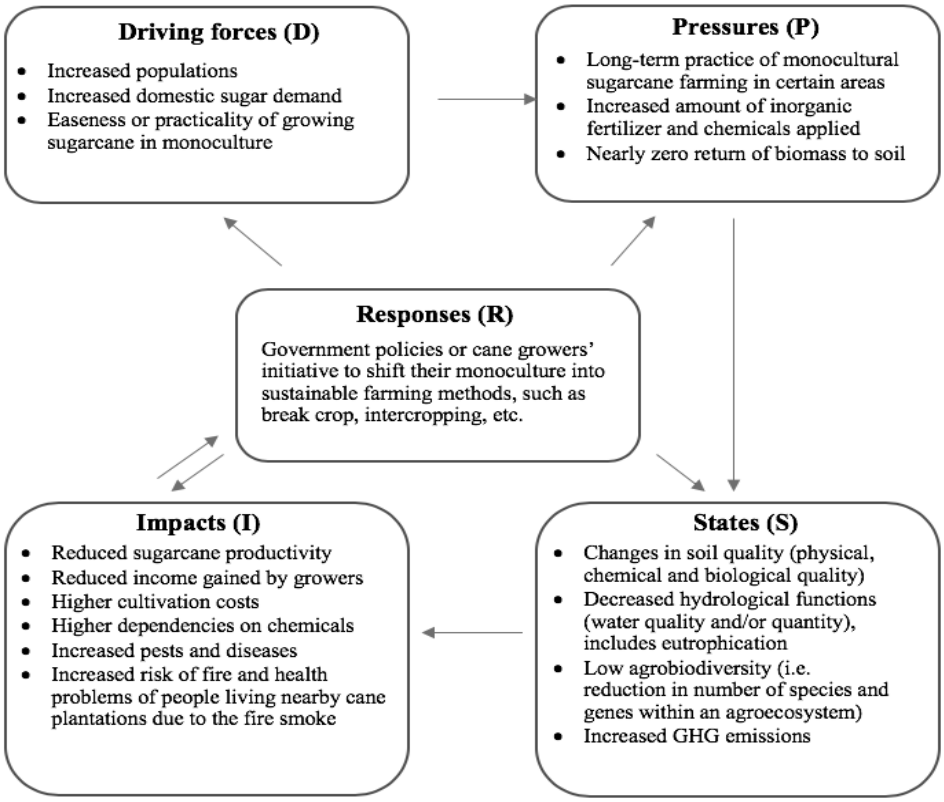

Figure 1. The DPSIR diagram of environmental problem caused by long-term sugarcane monoculture in Indonesia

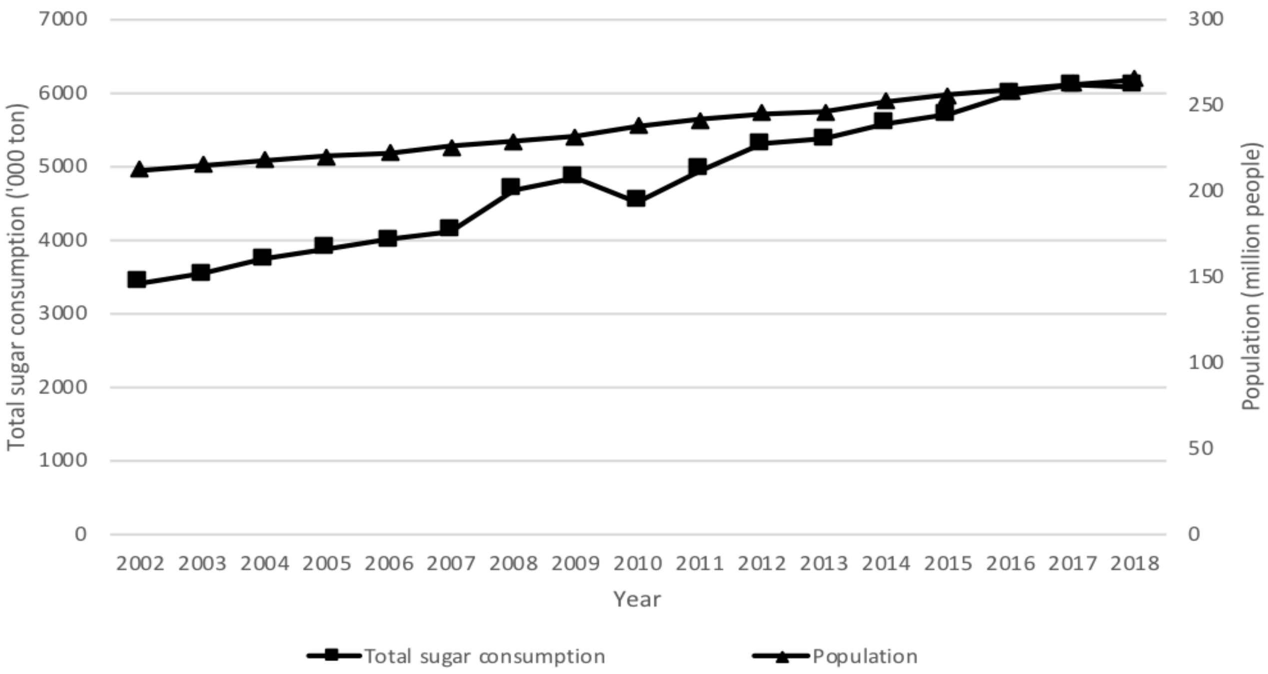

Figure 2. Total sugar consumption (direct consumption + industry) and population growth in Indonesia between 2002 and 2018 (adapted from NSC 2020; Toharisman and Triantarti 2016)

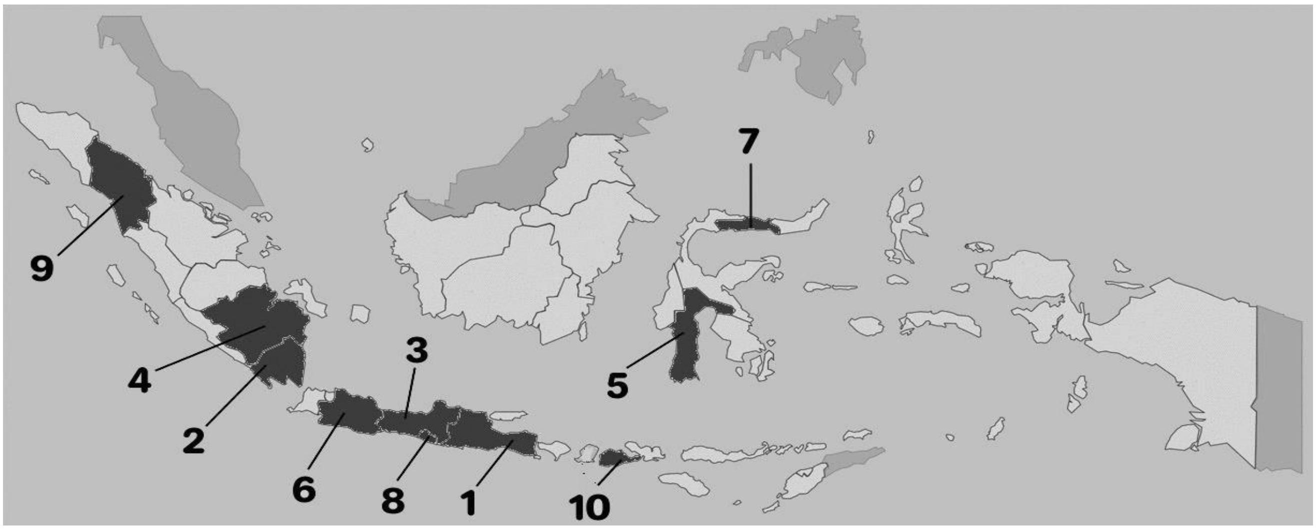

Figure 3. Map of sugarcane plantations distributions across Indonesia in 2018 (adapted from Statistics Indonesia 2018). Note: The numbers on the map show the provincial rank of plantation areas in Indonesia from the largest. 1. East Java (196,897 ha/ 47.4%), 2. Lampung (109,837 ha/ 26.4%), 3. Central Java (36,852 ha/ 8.9%), 4. South Sumatera (21,609 ha/ 5.2%), 5. South Sulawesi (14,636 ha/ 3.5%), 6. West Java (14,232 ha/ 3.4%), 7. Gorontalo (8,242 ha/ 2%)8. Special Region of Yogyakarta (6,805 ha/ 1.6%)9. North Sumatera (6,196 ha/ 1.5%)10. West Nusa Tenggara (357 ha/ 0.1%). After 2018, private companies expanded their sugarcane plantations in South East Sulawesi and East Nusa Tenggara.

Figure 2 indicates a close relationship between the growth of the population and total sugar consumption over time in Indonesia. At the beginning of 2002, total sugar consumption in Indonesia reached approximately 3.4 million tons, while the population was about 212 million people. The growth rate of sugar consumption exceeded the population growth and has become closer in 2016 onwards. In 2018, the total sugar consumption and the population number were about six million tons and 265 million people, respectively. This condition implies a linear correlation between population growth and total sugar consumption in Indonesia, which has become the main driving force for the implementation of sugarcane monoculture in the country.

Commercial sugarcane cultivation by monoculture in Indonesia was initiated by Dutch colonials in the 1830s. This adoption of a monoculture system mostly occurs in large-scale sugarcane plantations belonging to the state-owned companies (PT Perkebunan Nusantara/PTPN) or private sugar companies. Sugarcane monoculture in Indonesia often uses extensive synthetic chemicals such as inorganic fertilizers (mainly nitrogen) without considering the current soil nutrient status, as well as pesticides and herbicides (5-15 liter per hectare of ametrine-2,4-dichlorophenoxyacetic acid solution) to increase yield. Nitrogen addition, to some extent, support vegetative growth, leading to high biomass (Pawirosemadi 2011). Nevertheless, the situation is somewhat different if the sugarcane is grown by smallholder farmers. The smallholders are very ‘volatile’ as they may easily change the sugarcane into other crop commodities that are financially more profitable. However, even though the smallholders often suffer from financial losses, many of them still preserve their sugarcane plantations due to farming practicality, higher cost when changing into the other commodities, and an expectation to gain more profit in subsequent harvests (Idris 2016).

Sugarcane is commonly ratooned in Indonesia, and harvest continues for some years. Sugarcane ratooning is profitable as the growers can minimize production costs for soil tillage, seeds, and labor (Srivastava and Rai 2012). However, the maximum period of ratooning is only three years to make the method stays profitable for farmers. After three years, the yield of ratooned plantations tends to decreases and less profitable; thus, it should be re-plowed, and new sugarcane seeds should be planted (Pawirosemadi 2011). Until currently, most Indonesian sugarcane growers are still practicing ratooning for more than three times.

Sugarcane produces high biomass, consisting of stalks and leaves, approximately 100 tons per hectare, mainly from stalks processed into sugar. Sugarcane dry leaves, which account for 5-20 tons per hectare, are left at the field (Sandhu et al. 2017). In Indonesia, the residues are mostly subjected to be burned that may result in nearly zero biomass return to the sugarcane plantation.

States (S) of long-term monoculture of sugarcane farming in Indonesia

We have identified some possible ecological changes under long-term sugarcane monoculture in Indonesia. A natural land provides habitats for wildlife and serves multifunctional purposes to human life, such as for agriculture, pastoralism, infrastructure development, mining, tourism. It also provides a range of ecosystem services such as soil formation and retention, soil nutrient cycling, species maintenance, biological control, climate regulation, prevention of disturbance and moderation of extreme weather, water, air, and soil purification, and many more (Zari 2015). When a natural land is converted into sugarcane plantations, and a conventional monocropping system is applied for a long time, the ecological functions might be reduced. However, the extent to which long-term sugarcane gives drawbacks to the environment varies depending on the type or scale of production and its location (Hawkins 2018).

Decreased soil quality

Soil quality is the most affected factor caused by a long-term monoculture of sugarcane cultivation. An assessment of soil quality involves three different aspects, namely the physical, chemical, and biological properties of the soil. Soil physical properties refer to the soil morphology, such as texture, color, density, and porosity. The chemical attributes correlate to all chemical forms of the soil, such as pH, organic matter (OM) content, soil nutrient composition, cation exchange capacity (CEC), and chemical composition of the parent material.

Soil quality is greatly influenced by land management, where long-term sugarcane monoculture affects soil physical and chemical properties. Studies regarding the impacts of sugarcane monoculture on soil physical characteristics in Indonesia are scarce, but they are reported by numerous global studies. In a common sugarcane monoculture, for instance, the use of a natural groundcover is scarce, hence making soil erosion is prevalent in this system due to heavy rain or excessive furrow irrigation (Srivastava and Rai 2012). In an agroecological-managed system, a groundcover is usually cultivated along with main crops to protect topsoil from erosion and drought. Sugarcane cultivation can induce negative impacts on soil porosity (reduced 20% of soil total porosity indicator), soil organic carbon (reduced from 20 g/ kg to less than 15 g/kg), and soil aggregate stability (changed the micro, meso, and macro-porosity distribution) (Cavalcanti et al. 2020). Soil compaction can also occur in conventional sugarcane cultivation due to the intensive use of heavy machinery during planting and harvesting (Srivastava and Rai 2012; Hawkins 2018). Soil compaction can reduce water infiltration capacity in the soil and, therefore, can intensify erosion due to increased water runoff (Srivastava and Rai 2012). Highly compacted soil can also hamper root proliferation as affected by high mechanical resistance and poor aeration.

Long-term sugarcane monoculture can deplete soil fertility (Chi et al. 2017). Changes in soil physics due to intensive monoculture, such as loss of topsoil and soil compaction, lead to lower levels of nutrients and OM (Savario and Hoy 2011; Hawkins 2018), including soil carbon (Bordonal et al. 2017). Decreased soil quality is also caused by the burning practices of sugarcane residues before and following harvest (dos Santos et al. 2020). In continuous sugarcane monoculture, soil quality may become poor due to improper nutrient management (Srivastava and Rai 2012). Based on a field trial in Yogyakarta, Kusumawati et al. (2020) observed that soil pH and cation exchange capacity change with the prolonged duration of the sugarcane monoculture system in three different soil types. Continuous application of synthetic fertilizer in a monoculture system might also increase soil electrical conductivity (EC) and induce soil acidification. In the long-term duration, increased soil EC combined with low pH might adversely affect the yield and the quality of sugarcane. Furthermore, Pinheiro et al. (2010) found the changes in soil chemical parameters, i.e., pH, aluminum, as well as calcium and magnesium, over a 10-year cultivation period of sugarcane monoculture, particularly at a soil depth of 0-30 cm, corresponding to the fluctuated yield.

Decreased hydrological functions

Sugarcane requires a vast amount of water during its growth stage (Srivastava and Rai 2012; Sulaiman et al. 2019). A minimum of 12 to 18 Megalitre per hectare is needed for each growing season, while the crop water requirement (CWR) for sugarcane (1,950 mm/season) was almost doubled the rice's CWR for each growing season (1,004 mm/season) (Steduto et al. 2012). To a certain extent, long-term sugarcane monoculture could reduce water availability (Silalertruksa and Gheewala 2018; Sulaiman et al. 2019; German et al. 2020). The absence of water use regulation and management can lead to fierce competition between water users, i.e., local community, natural ecosystems, or growers of the other crops, and sugarcane growers (Sulaiman et al. 2019; Ranomahera and Ritzema 2020). The water supply at the tail-end of the hydrological cycle might be affected severely. For instance, a decline in water quantity due to long-term sugarcane monoculture was reported in Indramayu, West Java (Ivansyah 2015). The condition, in turn, can hamper sugarcane growth since 80% of sugarcane plantations in Indonesia rely on irrigation (Sulaiman et al. 2019).

Sugarcane monoculture can also lead to the water pollution caused by chemicals, i.e., fertilizers, pesticides, or herbicides flowing into water bodies (Davis et al. 2011; German et al. 2020). The other minor contributors of eutrophication in a sugarcane plantation are NO_x (nitrous oxide) from sugarcane burning, transportation, and machinery operation (Renouf et al. 2010). The decline of water quality may impact both freshwater and marine ecosystems (Hawkins 2018). In Mojokerto, East Java, there was a report of a quality decline of well water nearby a sugarcane plantation (Budianto 2018). When the water body is rich in nutrients, eutrophication may occur. Purwaningsih (2016) found multiple causes of eutrophication occurred on the water bodies near a sugarcane plantation in Subang, West Java, but P runoff due to TSP, NPK, and SP-36 fertilization is the greatest contributor to the problem.

Lowered agrobiodiversity

Agrobiodiversity refers to the variety of species and/or genetic of living organisms within an agroecosystem that plays a vital role in sustaining the ecosystem and in improving crop productivity. Several studies indicated a decrease in agrobiodiversity due to long-term sugarcane monoculture (Netondo et al. 2010; Mwavu et al. 2016; Hawkins 2018). In Malang, East Java, Nurhidayati et al.

(2011) found a decline in the earthworm population under long-term conventional sugarcane farming. They posited that the condition might be associated with reduced OM content and the use of mechanical tillage in the system. OM is important for earthworms and the other beneficial soil macrofaunas, hence the absence of OM in the soil can limit the growth and reproduction of those biotas (Medina-Sauza et al. 2019). Whereas the extensive implementation of the tillage system, such as plowing, can severely damage earthworm populations. Sugarcane monoculture systems can also decimate the population of beneficial microbes in the soil (Savario and Hoy 2011).

Increased Green House Gas (GHG) emission

de Figueiredo et al. (2010) observed that the most drastic GHG emissions during sugarcane farming have resulted from residues burning (44%), followed by synthetic fertilization (20%), and fossil fuel combustion from vehicles used to transport sugarcane to sugar factories (18%). Many Indonesian sugarcane growers burn their plantations before harvesting. At the field level, the burning method poses a dilemma since it can cut labor costs, enable manual workers to harvest sugarcane stalk more easily and quickly, as well as avoid the workers from personal injuries during harvesting. However, at the same time, the burning method of harvesting also causes air pollution (Pongpat et al. 2017). GHG emission in sugarcane fields also comes from the application of manure or inorganic fertilizer, especially N (Galdos et al. 2010; Luo et al. 2016; Wang et al. 2016). Burning method of sugarcane harvesting releases immense levels of GHG, as part of agricultural activities that recorded an increase of GHG emissions from 300 Mt CO_2e/year in 1990 to 800 Mt CO_2e/year in 2015, contributing to 5.3 % share of global GHG emissions (Brown to Green report 2017), such as carbon monoxide (CO), ozone (O_3) (Hawkins 2018), methane (CH_4), and N_2O (Galdos et al. 2010). Based on a field trial in Pati, Central Java, Hervani et al. (2017) discovered an average increase of N_2O gas fluxes of 843 μg N_2O/m/day in rainfed sugarcane area due to N fertilization. However, they also suggested that the emission produced depends on the interaction between soil type, climate, and cultivation technique.

Impacts (I) of long-term monoculture of sugarcane farming in Indonesia

The aforementioned explanation about the “States” induces several situations that will be described as “Impacts”. Degraded ecological conditions and lower agrobiodiversity due to long-term sugarcane monoculture are associated with the decreased yield (Altieri et al. 2015) and commercial cane sugar (CCS) (Djajadi 2015). Sugarcane productivity in Bungamayang, North Lampung, and Ogan Ilir, South Sumatera, for instance, has been fluctuating or even declining over time since the beginning of cultivation in 1984. This condition is associated with soil quality degradation, particularly the reduction in soil fertility (Premono et al. 1999). Another example of a gradual decrease in productivity happened in some cultivation areas in Java Island despite that the soils in these places have higher soil fertility. Indeed, areas with high soil fertility can sustain monoculture with reasonably high yields, but numerous studies have shown that after some time, the yields start declining.

Data explicates that Indonesia's sugarcane productivity decreased over time, although the sugarcane plantation areas are expanded (Figure 4). For the last thirty years, to support the plantation development, ISRI has focused on providing high sugar-yielded and agro-specific sugarcane varieties through breeding programs. Nonetheless, it is imperative to know that land degradation is not the only cause of such decline. There may be multiple and complex factors causing the decrease of sugarcane productivity over time in Indonesia. These include the occurrence of climate change or extreme weather, the emergence of new crop diseases and biosecurity issues, the lack of excellent sugarcane varieties, the lack of research and coordination amongst stakeholders in the sugar industry, etc. (Toharisman and Triantarti 2016).

Long-term sugarcane monoculture might gradually increase the cultivation costs. An annual survey of sugarcane cultivation costs conducted by several institutions, such as government agency, sugar industry, university, and ISRI, reported that during 2017-2018 there was a rise of about 15% in sugarcane cultivation costs (Directorate General of Estate Crops 2017-2018, unpublished report). The decline of soil quality in long-term sugarcane monoculture forces the growers to increase their agronomic inputs such as inorganic fertilizers and chemical pesticides to maintain high productivity.

A combination of long-term monoculture system, the application of chemicals, and the use of certain dominant sugarcane cultivar has contributed to the increased emergence of pests and diseases in the sugarcane cultivation. Currently, there are several reports indicated an increase of pests and pathogens attacks in sugarcane fields over Java and Sumatera Island (ISRI 2019, unpublished report). In Sumatera Island, for instance, *Xylaria* spp., which is a pathogenic fungus, has spread over thousands of hectares of sugarcane plantations. While in Java Island, the spread of leaf disease become more prevalent in the plantations cultivated by a certain dominant sugarcane cultivar. Lower agrobiodiversity is also responsible for increased pests infestation due to reduced pest natural enemies. Increased vulnerability of sugarcane to pests and pathogens in long-term monoculture systems leads to a higher dependency on chemicals such as pesticides and fungicides. Consequently, growers need to spend higher cultivation costs to buy the chemicals, which at the same time, income gained by the growers might be lower due to reduced yields.

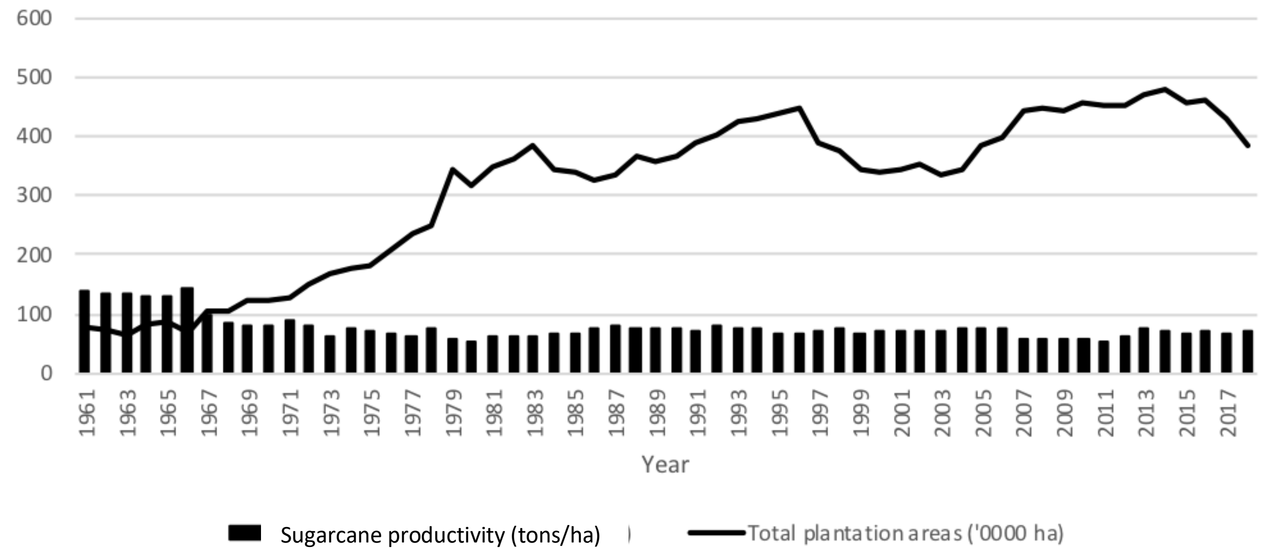

Figure 4. Sugarcane productivity and sugarcane plantation areas in Indonesia between 1961 and 2018 (adapted from ISRI 2004; Directorate General of Estate Crops 2016; FAOSTAT 2020; Indonesian Ministry of Agriculture 2020; Our World in Data 2020)

The practice of sugarcane monoculture also enhances the risk of fire in the plantation, especially in dry seasons or when the residues are dry. Fires in the plantations can be triggered by wildfires such as lightning or human activities on site. In some locations, sugarcane trashes are deliberately burned to ease manual cutting (Gonino et al. 2019). Smoke and ash particulate of the fire is often jeopardizing the health of plantation's workers or people living nearby the plantations (Cristale et al. 2012; Mnatzaganian et al. 2015; Paraiso and Gouveia 2015; Le Blond et al. 2017; Leite et al. 2018). Ash produced from sugarcane trash burning can also adversely affect fish species living in the surrounding aquatic systems (Gonino et al. 2019).

Response (R) of long-term monoculture of sugarcane farming in Indonesia

Response refers to the actions adopted by the relevant stakeholders, i.e., sugarcane growers, companies, and government to overcome environmental problems and yield decline in the sugarcane monoculture plantations in Indonesia (Table 1). The incorporation of ecological practices into sugarcane cultivation management can alleviate the adverse effects of monocropping on environmental degradation and yield decline. Land management measures should be directed to address the trade-off between economic development and greater biodiversity sustainability (Beza and Assen 2017). The Indonesian government can offer a set of policies and instruments related to the strategies, while initiatives from sugarcane growers are also important.

Crop break or crop rotation with legume or other crops

Breaking sugarcane monoculture by growing legumes or other plants in rotation can be beneficial for the environment and crop growth. Biomass from the plant in the rotation system can be used as a green fertilizer if incorporating into the soil. Crop break or rotation can improve soil fertility, primarily if legume is used (Park et al. 2010; Stirling et al. 2010). This practice can also help break the pests and pathogens cycle (Stirling et al. 2010), controlling root pathogens, leading to an increase of 11-30% of sugarcane yield (Ambrosano et al. 2013).

Although the use of green fertilizer by the sugarcane growers is uncommon, it is not a new practice in Indonesia. In the past, many sugarcane farmers used to plant breaking crops before sugarcane planting or after ratoon unloading. During the Dutch colonial era, sugarcane growers in Jombang and Kediri, East Java, often employed *Crotalaria juncea* as green fertilizer. However, with the growing practice of sugarcane monoculture, there is limited space and time to plant such green fertilizer. Sugarcane growers are currently more dependent on inorganic fertilizers (Djajadi 2015). Sugarcane growers may also become indolent in applying green fertilizer since they need to spend money on removal of sugarcane stumps, soil tillage, and planting (Srivastava and Rai 2012; Ambrosano et al. 2013). Besides, the positive impacts of crop break cannot be seen immediately. It took some time for nitrogen from legume to be mineralized and available for sugarcane in a legume-sugarcane rotation system (Park et al. 2010).

Intercropping

In sugarcane cultivation, intercropping can be done right after soil tillage or planting time up to three or four months following planting time. After this period, sugarcane canopy will grow larger, and sunlight cannot penetrate; thus, another crop cannot grow optimally under the shade. Intercropping of sugarcane with legume or other crops can improve soil structure and fertility (Li et al. 2012). Yang et al. (2013) found that sugarcane intercropping with soybean improves land and nitrogen use efficiency compared to sugarcane monoculture. Several studies reported an increase of sugarcane yield in intercropping with soybean (Luo et al. 2016; Wang et al. 2020) because sugarcane gets additional nitrogen. Legumes can establish symbiosis with Rhizobium bacteria to fix nitrogen from the atmosphere. Intercropping can also help in improving soil microbial diversity (Li et al. 2012; Solanki et al. 2019) and its activity (Solanki et al. 2019), increasing AMF (Zhang et al. 2020), as well as providing extra economic benefits to sugarcane growers (Chagas et al. 2015; Teshome et al. 2015; Ullah et al. 2017; Shukla et al. 2019; Nadeem et al. 2020).

Table 1. Summary of possible crop management modifications to mitigate the adverse impacts of sugarcane monoculture

Crop management options	Reported benefit(s) from previous worldwide studies	Reported disadvantage(s) from previous worldwide studies
Crop break or crop rotation with legume or the other crops	• Fixing atmospheric nitrogen to the soil if legume is used; thus increasing total N to the soil (Park et al. 2010; Stirling et al. 2010) • Breaking pests and pathogens cycle (Stirling et al. 2010) • Controlling root pathogens (Ambrosano et al. 2013) • Enhancing sugarcane growth (Ambrosano et al. 2013)	• Cash is needed to demolish sugarcane stumps, soil tillage, and planting (Srivastava and Rai 2012; Ambrosano et al. 2013) • The positive impacts cannot be seen immediately (Park et al. 2010)
Intercropping	• Improving soil structure and fertility (Li et al. 2012) • Improving land-use efficiency (Yang et al. 2013) • Enhancing soil microbial diversity (Li et al. 2012; Solanki et al. 2019) and activity (Solanki et al. 2019), as well as arbuscular mycorrhizal fungi (AMF) (Zhang et al. 2020) • Increasing sugarcane yield (Luo et al. 2016; Wang et al. 2020) • Providing extra economic benefits to growers (Chagas et al. 2015; Teshome et al. 2015; Kaur et al. 2016; Ullah et al. 2017; Shukla et al. 2019; Singh 2020)	• Potentially reducing sugarcane yields due to competition between sugarcane and the other crops (Layek et al. 2015)
Green harvesting and trash blanket	• Maintaining or improving soil organic carbon and the other nutrients (Singh et al. 2012; Trivelin et al. 2013; Shukla et al. 2016; Sandhu et al. 2017; Bordonal et al. 2018; Luca et al. 2018; Castioni et al. 2019) • Improving soil physical quality attributes, such as increasing soil water-stable aggregates (Surendran et al. 2016) and preventing soil compaction (Castioni et al. 2018) • Avoiding sudden fluctuations in soil temperature (Awe et al. 2015) • Preserving soil moisture (Liao et al. 2013; Nxumalo et al. 2016; de Aquino et al. 2017; Castioni et al. 2018; de Castro et al. 2018; Corrêa et al. 2019) • Increasing water use efficiency (Ng Cheong and Teeluck 2015; Dhanapal et al. 2018) • Reducing weed growth and costs for it (Tortora et al. 2013) • Enhancing earthworm populations (Castioni et al. 2018) • Increasing sugarcane yield (Surendran et al. 2016; Singh et al. 2012; Liao et al. 2013; Ng Cheong and Teeluck 2015; Nxumalo et al. 2016; de Aquino et al. 2017; de Aquino et al. 2018; Bordonal et al. 2018; Dhanapal et al. 2018; Corrêa et al. 2019) • Reducing GHG emissions if residues are not burned before or after harvesting (Pryor et al. 2017)	• Escalating risk of fire within sugarcane plantations (de Castro et al. 2018) • Increasing pests and pathogens proliferation (de Castro et al. 2018) • Increasing GHG emissions (do Carmo et al. 2012; Wang et al. 2016) • Higher labor costs if manual green harvesting method is applied (Junpen et al. 2020)
Precision agriculture (PA)	• Lowering environmental impacts (Prasara-A and Gheewala 2016) • Reducing input and production cost (Prasara-A and Gheewala 2016) • Increasing sugarcane yield and quality (Silva et al. 2011)	• High technology and services costs (Silva et al. 2011; Pedersen and Lind 2017) • Adequate information and knowledge to operate PA's technologies are needed (Silva et al. 2011; Pedersen and Lind 2017)
Organic matter (OM) amendment	• Many OM types can be used, including filter cake (by-product of sugar mills) and vinasse (by-product of sugarcane-based bioethanol distilleries) (Djajadi 2015; Dotaniya et al. 2016) • Improving soil quality (chemical, physical, biological) (Jiang et al. 2012; Prado et al. 2013; Dotaniya et al. 2016; dos Santos et al. 2020) • Increasing the abundance of soil biota, including soil microbes (Balota and Auler 2011; Nair and Ngouajio 2012; Neher et al. 2013; van Horn et al. 2013; Zaccardelli et al. 2013; El-Sharouny 2014; Zhen et al. 2014; Sun et al. 2015; Francioli et al. 2016; Spiegel et al. 2018; Zhu et al. 2020) and fungi (Miura et al. 2013; Yang et al. 2018) • Enhancing sugarcane yield and quality (Dotaniya et al. 2016)	• Some OM types such as untreated filter cake or vinasse lead to environmental pollution (Prado et al. 2013), includes GHG emission (do Carmo et al. 2012)

Although intercropping is beneficial, it can also potentially reduce sugarcane yield. Some preliminary studies discovered a lower yield of sugarcane grown in an intercropping system than monoculture, although the differences are insignificant (Layek et al. 2015; Ullah et al. 2017). This condition can be occurred due to competition for solar radiation, as well as nutrients and moisture in the soil between sugarcane and the other crops (Layek et al. 2015). Therefore, it is necessary to choose 'suitable' crops intercropped with sugarcane.

Green harvesting and trash blanket

Sugarcane plantations produce many residues (trashes) that can be potentially used as organic fertilizers. However, such potential has not been fully exploited by most Indonesian sugarcane growers.

Many growers prefer to burn sugarcane residues prior to harvesting to make the harvesting process easier, faster, and convenient. However, implementing the burning practice in sugarcane plantation means 'throwing away' organic matter from the plantation.

Sugarcane residues have an important role in sustaining soil functions (Castioni et al. 2018). By implementing green harvesting and trash blanket method, trashes or residual sugarcane biomasses are returned back to the plantation as fertilizer. Sugarcane residues are essential sources of carbon and other nutrients such as minerals hence it can maintain or even improve soil fertility (Singh et al. 2012; Trivelin et al. 2013; Shukla et al. 2016; Bordonal et al. 2018; Luca et al. 2018; Castioni et al. 2019). Trash blanket also increases the abundance of soil-dwelling organisms, such as earthworms (Castioni et al. 2018). An increased number of earthworms can help in regulating soil structure (Sharma et al. 2017; Frazão et al. 2019) and play a role in the soil nutrient cycling process through decomposition and mineralization (Lubbers et al. 2010; Bernard et al. 2012; Domínguez and Gómez-Brandón 2013; van Groenigen et al. 2014; Wachendorf et al. 2014; Waqar et al. 2019); thus, it leads to reduced fertilizer requirements. Previous studies showed an increase in sugarcane yield due to the implementation of trash blanket (Surendran et al. 2016; Singh et al. 2012; Liao et al. 2013; Ng Cheong and Teeluck 2015; Nxumalo et al. 2016; de Aquino et al. 2017; de Aquino et al. 2018; Bordonal et al. 2018; Dhanapal et al. 2018; Corrêa et al. 2019). If the trash blanket method is implemented continuously in a sugarcane plantation, beneficial soil biota will create a positive feedback system with continuous soil fertility improvements. In Lampung, Salamah et al. (2016) found a higher earthworm population in sugarcane plantation under organic mulching treatments than that of non-mulching treatments. However, the magnitude of the positive impacts of trash blanket implementation depends on the amounts of residues, climate, and soil types in the plantation, as well as crop management (Castioni et al. 2018). Carvalho et al. (2017) suggested that the positive impacts of implementing a trash blanket are attained when at least seven tons per hectares of trashes are maintained on the soil surface.

To implement the trash blanket, sugarcane residues should firstly be cut into small pieces. It can be done manually or mechanically by using a rotary mulcher and trash shredder. Then, the cut residues are used as soil cover over the plantations. This can be done manually or mechanically using hay rake and wheel trash rake (Nalawade et al. 2018).

Although there are numerous benefits of implementing a trash blanket, there are also some drawbacks of applying trash blankets, such as the increased risk of fire and higher proliferation of sugarcane pests and pathogens (de Castro et al. 2018). If manual harvesting without prior burning is performed, a higher labor cost is also needed (Junpen et al. 2020). Even so, these costs can be possibly compensated by reduced fertilizer costs and increased sugarcane productivity in the long run.

Precision agriculture (PA)

Precision agriculture (PA) allows growers to irrigate and fertilize their crops using a precise amount of water and fertilizers at the right time, in accordance with the actual field condition (Shafi et al. 2019). The use of optimal quantities of fertilizers and pesticides in PA can lower the environmental impacts and lessens production costs without compromising the sugarcane yields (Silva et al. 2011; Prasara-A and Gheewala 2016). PA can also minimize eutrophication effects on water bodies near sugarcane plantations. Furthermore, this method can contribute to the agricultural water use efficiency to maintain the hydrological functions. Among the examples of PA technologies applicable for sugarcane plantation are automatic planters or harvesters, satellite images, aerial photography, georeferenced soil sampling, satellite steering system, weed, and disease sensors, as well as soil electrical conductivity sampling (Silva et al. 2011).

Although PA offers some benefits to sugarcane growers, relatively higher investment is required to purchase PA-related technologies as well as for their maintenance. Besides, adequate knowledge on how to operate the PA's technologies is needed (Silva et al. 2011; Pedersen and Lind 2017). PA relies on the collection, analysis, processing, and synthesis of comprehensive georeferenced data (Driemeier et al. 2016). This can become a barrier for Indonesian sugarcane growers, especially smallholders, who do not even have access to the basic information regarding the technology. However, PA can still be possibly performed by large Indonesian sugarcane companies, such as private companies and PTPN, since they often have adequate capital and human resources.

Organic matter (OM) amendment

By far in Indonesia, OM is rarely amended into sugarcane plantations since growers prefer to use inorganic fertilizers. For instance, some of PTPN have applied filter cake and the other types of OM to their sugarcane plantations. However, the application is limited to a small scale and not fairly distributed throughout the estates. In general, Indonesian sugarcane growers may not prefer the soil amendment with OM since the positive effects of the OM cannot be seen immediately. Sugarcane growers in Kediri and Jombang, East Java, experienced that their sugarcane-cultivated soil becomes harder, and additional urea is needed due to the OM amendment. However, this might be a short-term effect as the chemical, biological, and physical aspects of soil are reported to be improved in the long-term OM application (Djajadi 2015).

Previous studies reported an increase in the abundance of soil organisms, including soil microbes due to OM amendments (Balota and Auler 2011; Nair and Ngouajio 2012; Neher et al. 2013; van Horn et al. 2013; Zaccardelli et al. 2013; El-Sharouny 2014; Zhen et al. 2014; Sun et al. 2015; Francioli et al. 2016; Spiegel et al. 2018; Zhu et al. 2020) and fungi (Miura et al. 2013; Yang et al. 2018). Consequently, these microbes contribute to nutrient cycling processes and aggregate formation (Rashid et al. 2016). Several beneficial soil biotas, such as bacteria and fungi, are categorized as plant-growth-promoting microbes (PGPM). These microorganisms can enhance plant growth performance. PGPM can regulate plant hormones, produce siderophore, improve the antioxidant system, and increase nutrient acquisition in plants (Kumar and Verma 2018). They can also induce resistance of sugarcane against pests and pathogens as well as several abiotic stresses, such as soil salinity and drought (Naik et al. 2019).

Several types of OM can be used as soil amendments in sugarcane plantation, such as green composts, manure, biofertilizers, or a combination of them (Djajadi 2015). By-products produced from sugar mills and sugarcane-based bioethanol distilleries such as filter cake, bagasse, and vinasse can also be used as OM. However, such by-products should be firstly treated or composted before used; or otherwise, it can cause environmental pollution. Raw filter cake or vinasse has a low pH, high biological oxygen demand (BOD), and high chemical oxygen demand (COD) (Prado et al. 2013). Besides, similar to inorganic fertilizer, some OM types such as manure, filter cake, and vinasse might also potentially emit GHG emissions (do Carmo et al. 2012). Furthermore, it should be taken into account the proper dosage and timing of application to minimize the emissions.

Indonesian sugarcane growers are suggested to implement one or a combination of several management options mentioned before (Table 1); hence, achieving both environmental and economic sustainability is possible. The growers should decide which practice fits best for their plantation since each crop management has drawbacks. Besides the five aforementioned crop managements, many researchers also suggest a minimum or zero tillage conserve soils under monoculture (Palm et al. 2014). Nevertheless, the implementation of this method is nearly impossible to be implemented in the Indonesian sugarcane plantations due to the rooted habit of extensive soil tillage among sugarcane growers, unless there is an adequate knowledge amongst the growers regarding the benefits of zero-tillage implementation.

The present study only emphasizes on the environmental impacts of the sugarcane monoculture in Indonesia. Other than that, there are also some positive impacts of the system on socio-economic factors that are not included in the DPSIR framework. For instance, monocultures may create job opportunities. This is because generally, the sugar production process, from sugarcane cultivation to processing in the sugar mill, often requires high labors. Besides, the sugarcane monoculture system also supports the continuity of sugarcane supply for sugar mills in Indonesia.

To conclude, a conventional monoculture is still practiced by sugarcane growers in Indonesia, especially by large sugar companies. Smallholder growers are more flexible since they may change their crops to other commodities that are more profitable. However, most of them still preserve their sugarcane plantations due to farming practicality, lower production cost, and an expectation to profit in subsequent harvests. It is obvious that the main underlying drivers are population factors and the rise in sugar demand over time. On one side, it helps to fulfill domestic sugar demand in Indonesia. Notwithstanding, the conventional method of sugarcane cultivation in long-term duration contributes to decreased soil quality and some environmental problems, leading to reduced productivity of sugarcane. Since it is difficult to make such a trade-off between sugar production and environment, sustainable sugarcane cultivation management can serve a win-win solution, i.e., crop break or crop rotation, intercropping, green harvesting and trash blanketing, and PA. Each of them has advantages and disadvantages, so sugarcane growers must consider which management practice best fits their plantation.

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