

# Sustainability assessment of ecological intensification practices in coconut production<sup>☆</sup>

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## ABSTRACT

Environmental impact and economic performance assessments are important subjects for the definition of strategies for sustainable management in agriculture. The objective of the present study was to assess such impacts in a set of reference farms dedicated to coconut production, conforming a gradient with respect to the adoption of technologies and ecological intensification practices. Ranging in scale from smaller family farms to larger corporate enterprises, and from coconut monocultures to diversified crops and integrated coconut-livestock systems, the six cases were studied through a multi-attribute utility model comprising 62 indicators related to five sustainability dimensions: (i) Landscape ecology, (ii) Environmental quality, (iii) Sociocultural values, (iv) Economic values and (v) Management and administration. Detailed cash flow analyses permitted a critical view regarding the influence of technology adoption, ecological intensification, and management for sustainability as criteria for economic viability. The results attest to the value of produce diversification as opportunity toward technology integration, which correlated positively with higher sustainability indices in all dimensions. Tradeoff analysis showed a negative correlation between socio-environmental performance indices and profitability, whereas none of the cases studied showed constrained economic viability, indicating that ecological intensification in coconut production can also entail social improvements, by promoting fairer share of revenues and benefits among stakeholders. Recommendations issued to farmers and management teams, related with agronomic factors and practices adopted in production intensification, favor the communication of appropriate mechanisms for technology adoption, translating farm-level sustainability assessments into action for sustainability.

## 1. Introduction

World trade of coconut-derived products is expected to increase in the years to come. Technavio's market research (Technavio, 2016a, 2016b) forecasts that, during the period of 2016–2020, the global market will show a compound annual growth rate (CAGR) of around 27% and 15%, for tender coconut water and coconut milk, respectively. In its turn, Europe projects to record a CAGR of 4.7% for coconut oil in the 2017–2022 horizon, and the market for this product is anticipated to grow to more than US\$ 3 billion by 2022 (Fact, 2017). These market trends are being driven by increasing health-consciousness among consumers, as coconut water contains important electrolytes with

strong indications for health promotion (Radenahmad et al., 2011; DebMandal and Mandal, 2011; Radenahmad et al., 2012). In this broader movement of consumers seeking out healthier food and hydration products with simpler ingredients, coconut water has attracted the interest of world's giant companies of the beverage industry, which by means of modern packing techniques to increase the shelf life up to 18 months, are promoting a beach-to-bench approach to expand the market for tender coconut water from 100 million liters in 2012 to 350 million liters by 2020 (CBI, 2014). Similar market trends are also expected for other coconut-derived products, such as desiccated coconut meat, that showed a 102% increase in the European market in the last five years (CBI, 2015a), and virgin coconut oil (CBI, 2015b).

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**Table 1**  
 Technical and managerial characterization of the rural establishments selected for sustainability analysis, according to their respective ecological intensification and technology adoption contexts.

Rural establishment	Climate	Total and coconut planted areas, cultivation year	Diversification aspects	Management type	Intensification level/technology	Main product
Case 1	Köppen-Geiger: Am Mean T °C: <sup>2</sup> 24.8 Prec. <sup>3</sup> : 1791 mm	96 ha, 60 ha dwarf coconut <sup>4</sup> , started in 1998/9	No, dwarf coconut monoculture, irrigated	Family business	Medium/micro sprinkler irrigation, mulching, chemical fertilizer, chemical control	Green coconut 'in natura'
Case 2	Köppen-Geiger: Aw Mean T °C: 23.8 Prec.: 919 mm	890 ha, 270 ha dwarf coconut, started in 1998	Yes, dwarf coconut, citriculture, diversified fructiculture, horticulture	Family business	High/micro sprinkler irrigation, organic fertilizer, restriction on the use of pesticides, Integrated Fruit Production and EurepGAP certification <sup>7</sup>	Green coconut 'in natura'
Case 3	Köppen-Geiger: Aw Mean T °C: 25.2 Prec.: 1209 mm	181 ha, 141 ha dwarf coconut, started in 1999	No, dwarf coconut monoculture, irrigated	Enterprise	Medium/micro sprinkler irrigation, mulching, chemical fertilizer, chemical control	Green coconut 'in natura'
Case 4	Köppen-Geiger: Aw Mean T °C: 27.5 Prec.: 1208 mm	4532 ha, 2594 ha coconut, started in 1982 with tall coconut <sup>5</sup> and hybrid coconut <sup>6</sup> introduced in 1988	No, coconut monoculture, 42% tall coconut without management, 33% rainfed hybrid coconut under ecological management, 25% irrigated hybrid coconut	Enterprise	High/systematic elimination of chemical control of weeds, using rotary tilling and mowing; mulching; liquid limestone and reduced P application; fertigation; biological control of insects ( <i>B. bassiana</i> , DiPel), Rainforest Alliance certification	Industry, grated coconut and coconut milk
Case 5	Köppen-Geiger: Aw Mean T °C: 26.5 Prec.: 1194 mm	204 ha, 87 ha dwarf coconut, started in 1997	Yes, dwarf coconut, sugarcane, intensive integrated dairy production	Family business	High/micro sprinkler fertigation with liquid bovine manure compost, mulching, livestock integration, restriction in pesticide use, chemical fertilizers	Green coconut 'in natura'
Case 6	Köppen-Geiger: Af Mean T °C: 26.9 Prec.: 2547 mm	21,000 ha, 6000 ha coconut, started in 1976 (tall coconuts), replanted with hybrids coconuts in 1992/93	No, however with special attention to coconut breeding and genetic diversity	Enterprise	High/rainfed, chemical fertilizer, chemical control, reduction of chemical control of weeds, using mowing; mulching; Green manuring with kudzu; varietal diversification from own origin, focusing on productivity and plant health, animal traction harvest	Industry wide and diverse range of food products

<sup>1</sup> Köppen-Geiger stands for Köppen-Geiger climate classification system (Am: Monsoon, Aw: Wet savanna, Af: Rainforest).

<sup>2</sup> Mean T °C is the annual daily mean temperature in Celsius.

<sup>3</sup> Prec. Stands for the mean annual precipitation.

<sup>4</sup> Dwarf coconut: dwarf coconut cultivars.

<sup>5</sup> Tall coconut: tall coconut cultivars.

<sup>6</sup> Hybrid coconut: hybrid coconut cultivars (hybrids between tall and dwarf).

<sup>7</sup> EurepGAP is a common standard for farm management practice created by European supermarket chains and major suppliers. GAP is an acronym for Good Agricultural Practices.

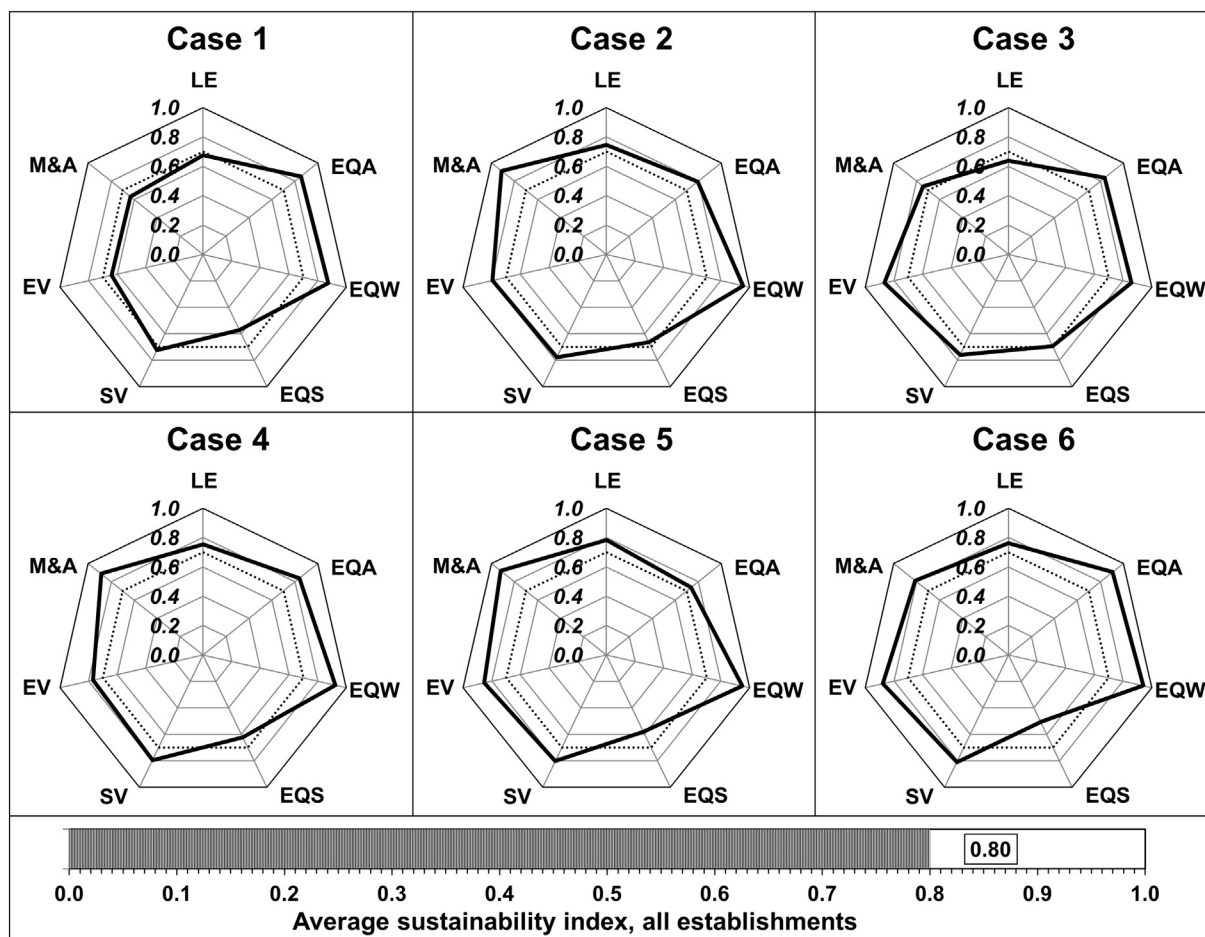


Fig. 1. Environmental performances for the six studied rural establishments dedicated to coconut production, for each sustainability dimension, according to the 62 indicators compiled in the APOIA-NovoRural impact assessment system. Indices are expressed in multi-attribute utility values. Also shown is the average sustainability index for all establishments. The dotted lines represent the 0.7 baseline compliance level. Sustainability dimensions: LE: Landscape ecology; EQA: Environmental quality/atm; EQW: Environmental quality/water; EQS: Environmental quality/soil; SV: Sociocultural values; EV: Economic values; M&A: Management and administration.

Even though the image of coconut is associated with Brazil, the country is only the fourth largest producer in the world. With around 2.8 million tonnes harvested in about 287,000 ha, its production is only just one-seventh that of the Philippines, the largest producer with 19.5 million tonnes; and far behind Indonesia with 15.3 million tonnes and India with 10.8 million tonnes (FAO, 2017). A main reason for the low coconut yield in Brazil (around  $11.3 \text{ t ha}^{-1}$ ) is that most production areas are typically extractive (Sobral et al., 2018) and over 70% of the establishments apply virtually no technology (Wanderley and Lopes, 2009). Brazilian production is primarily in the form of dried coconut, mostly directed to industrial products such as coconut meat and milk, with coconut water as co-product. In recent years the production of green coconut is increasing, with important expansion of areas planted with varieties suitable for the production of water, driven by the growth of consumption as a result of people's healthy habits.

Although present throughout the country, > 90% of Brazilian commercial coconut planted area occurs along the coast of the Northeast and part of the North (Ribeiro et al., 2010). Coconut production is an important employment and income generating activity, contributing significantly to the development of the producing regions. Special reference must be attributed to factors directly linked to the economic performance of coconut production, i.e., those that affect the quantity and quality of harvested fruits, determining profitability according to technological differences and crop-specific management practices (Pires et al., 2004). Even if most of the harvest is typically

extractive, coconut cultivation demands high technological levels to achieve adequate productivity, and high production costs have caused recurring crises in the industry, indicating the exhaustion of the conventional production model (Martins and Jesus Jr., 2014).

The costs associated with the necessary adoption of technologies to enable agriculture in general, and coconut production in particular, require that increases in production must come from higher levels of productivity, improving efficiency by the intensification of cultivation practices (Tilman et al., 2002). In the past, agricultural intensification was mainly a result of breeding, associated with increases in the use of inputs such as chemical fertilizers, pesticides, irrigation and mechanization (Matson et al., 1997).

Besides its adverse effects on the environment, this conventional practice is not in tune with the requirements of the 'smart consumers' and 'Millennial generation', the usually high-income consumer groups that are driving the trend in the food and beverage markets toward health and wellness products. These groups are socially and digitally connected and their consumption patterns demand transparency in all production processes (Kim, 2015), including ecologically friendly management practices and economic equity among all actors involved in the value chains (Askew, 2017; CBI, 2018). In order to meet these demands and circumvent those negative externalities, a current managerial trend known as 'agricultural ecological intensification' has been proposed, defined as the "maximization of primary production per unit area without compromising the system's ability to maintain its

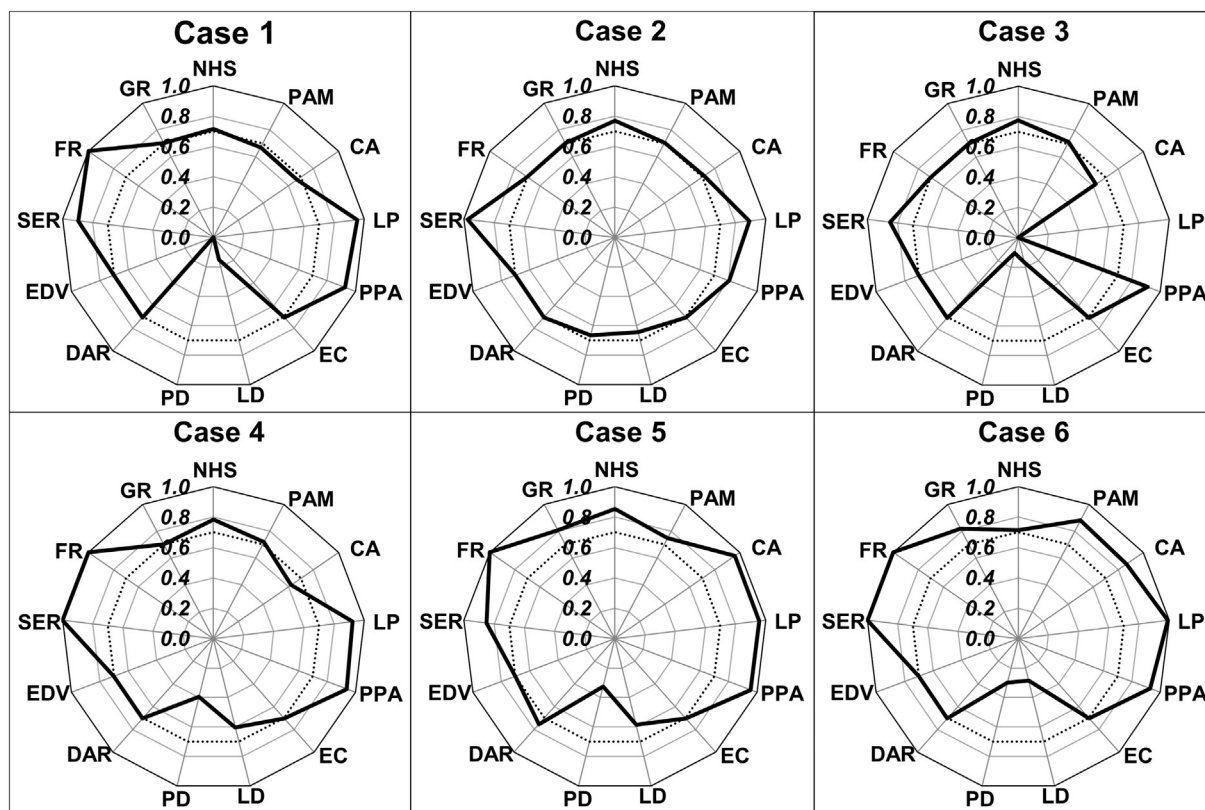


Fig. 2. Results for the Landscape ecology sustainability dimension, for the six studied rural establishments dedicated to coconut production. Data from the APOIA-NovoRural impact assessment system. The dotted lines represent the 0.7 baseline compliance level. Indicators: NHS: Natural habitats status; PAM: Productive areas management; CA: Confined activities, animal husbandry management; LP: Legal preserve; PPA: Permanent preservation areas; EC: Ecological corridors; LD: Landscape diversity; PD: Productive diversity; DAR: Degraded areas reclamation; EDV: Endemic disease vectors; SER: Species extinction risk; FR: Fire risk; GR: Geotechnical risk.

productive capacity” (FAO, 2009); or as “producing more food from the same area of land while reducing the environmental impacts” (Royal Society of London, 2009).

According to Griffon (2013), ecological intensification aims at enhancing biological regulations and ecological functions of ecosystems for the benefit of agricultural production. Therefore, it sets up as an option to solve the dialectical paradox in the current agricultural paradigm, offering a scientific basis for the development of an “ecological agribusiness”. Thus, ‘Ecologically Intensive Systems’ (EIS) have been a central reference to promote diversification of agricultural activities, as well as for the development and adoption of integrated techniques and management practices aimed at producing food in line with the environmental conditions and the local availability of natural resources, focusing on economic profitability, with parsimony in the use of external inputs and lower production costs (Wezel et al., 2015). Therefore, while agricultural sustainability is a goal to be achieved, ecological intensification sets up a set of management practices aiming to reach this goal.

In this context, an environmental performance assessment is an inescapable step for evaluating the effectiveness of agricultural management in promoting sustainability through ecologically intensive practices and a wide variety of methodological approaches have been developed to meet such a growing international demand for sustainability assessment (Van Passel and Meul, 2012; De Olde et al., 2016). Among these methodologies, the ‘system for weighted environmental impact assessment of rural activities’ (APOIA-NovoRural - Rodrigues and Campanhola, 2003) has been applied as an environmental assessment and management tool to an ample variety of agricultural sectors, in different countries and socioeconomic farming contexts, and several scales and contrasting production settings, and sets up as a consolidated

system for sustainability assessment of farming systems (see a review in Rodrigues et al., 2010).

Lack of understanding of production cost components and the economic impact of technology adoption hinder their incorporation and adequate evaluation, according to the diverse production systems observed in different environmental and managerial contexts. In the present research, we seek to identify the technological adoption contexts in which environmental performance gains are obtained, favoring the recommendation of ecologically intensive practices that promote sustainability in coconut production. Therefore, the objective of this study is to analyze the economic and environmental performances of coconut production in different technological contexts, as to identify the conditions and factors by which changes toward ecologically intensive practices have had greater potential to promote sustainability.

## 2. Material and methods

In the present research, the APOIA-NovoRural was utilized for the assessment of environmental performance of coconut production in Brazil. The method consists of 62 indicators grouped into five sustainability dimensions, namely: (i) Landscape ecology, (ii) Environmental quality (atmospheric emissions, water and soil), (iii) Socio-cultural values, (iv) Economic values and (v) Management and administration. The integrated indicators are organized in a set of multi-attribute utility weighting checklists, in which the performance indices are normalized from 0 to 1 and the conformity baseline modeled at 0.7, allowing quantitative and objective analysis of sustainability in field surveys carried out with analytical instrumentation and management data obtained with the farmers (Rodrigues et al., 2010).

For the indicators of the Landscape ecology dimension,

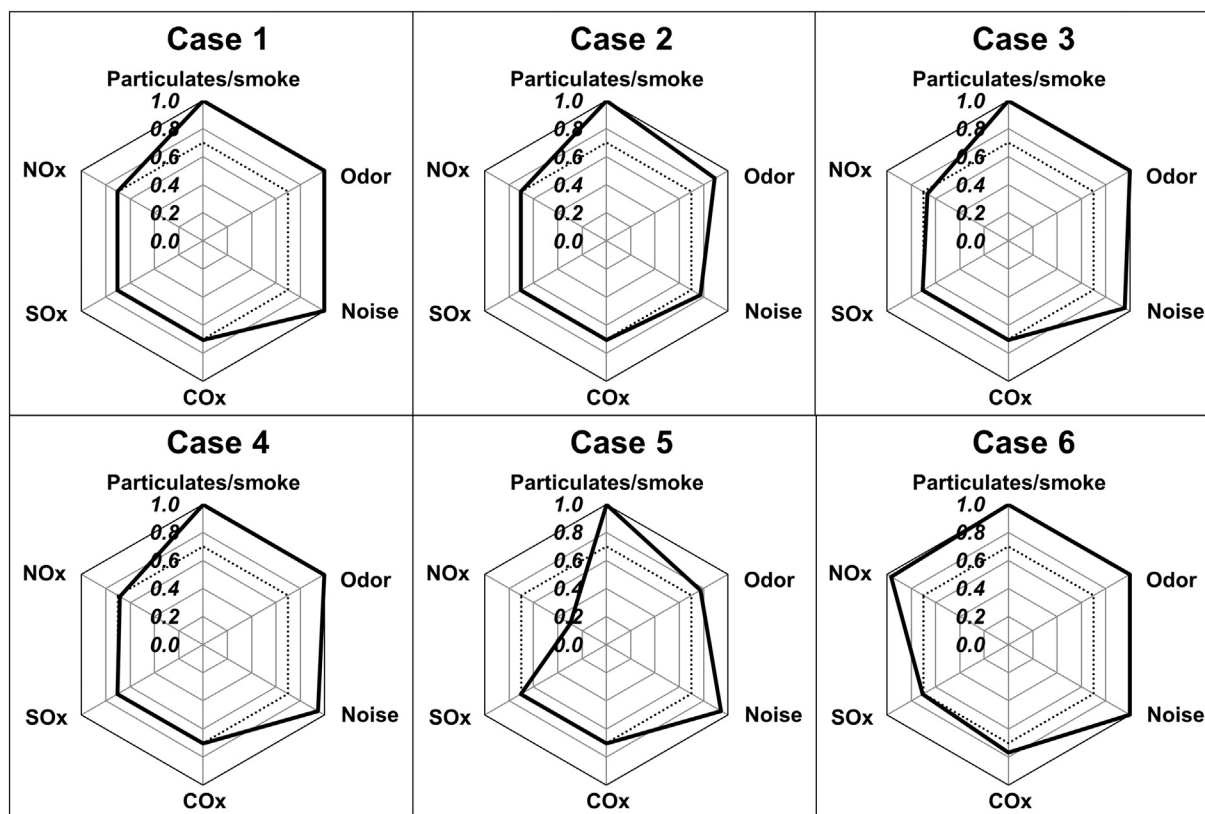


Fig. 3. Results for the Environmental quality sustainability dimension, atmospheric emissions indicators, for the six studied rural establishments dedicated to coconut production. Data from the APOIA-NovoRural impact assessment system. The dotted lines represent the 0.7 baseline compliance level.

geoprocessing techniques (using GPS, maps and satellite images) are applied to identify the accesses, limits and infrastructure, as well as bases for the calculation of agricultural land uses, physiognomy and conservation status of natural habitats and ecological corridors, fire and geotechnical risks (Frohn, 1998). Indicators related to water and soil quality are obtained in field and laboratory analyses. Water quality indicators ( $O_2$ , pH, conductivity, chlorophyll, turbidity) are analyzed in the field with multi-parameter probes (Horiba and YSI), nitrate and phosphate with field colorimeter Merck Rqflex (Rodrigues et al., 2013), fecal coliforms are estimated with Tecnobac culture stripes (Alpha-Tecnoquímica), water samples are analyzed in the laboratory for determination of Biochemical Oxygen Demand ( $BOD_5$ ) (Xinglong and Boyd, 2005) and soil samples are sent to reference laboratories for determination of chemical properties (Soil Organic Matter, pH, P, K, Ca, Mg, H + Al, and derived indicators Sum of Bases, Cation Exchange Capacity and Bases saturation) (Embrapa, 1997).

Indicators of the dimensions 'Economic values', 'Sociocultural values' and 'Management and administration' are obtained through document reviews and interviews with farmers/farm managers. Once compiled in the multi-attribute weighting checklists, the results are presented in graphs for each dimension, allowing the investigation of the indicators' roles in the performance of adopted practices and technologies. The average results in all dimensions are then expressed in a synthesis sustainability graph for the rural establishment.

Besides the socio-environmental performance indicators, the determination of production costs and profitability in the present study was individually tailored to the contrasting coconut production systems, based on the main agronomic activities, according to the methodology employed by Matsunaga et al. (1976). Data collection was divided into characterization of the rural enterprises and detailed information about the technical itineraries employed in coconut cultivation. The technical coefficients used were established in five groups comprising the proposed annual cost model: (i) fertilizers; (ii) pesticides

(fungicides, insecticides, herbicides, miticides) and other pest control inputs; (iii) manual operations; (iv) mechanized operations and (v) administrative expenses.

The sampled coefficients depict the situation of coconut orchards in full production. The prices taken to calculate depreciation of used inputs, machinery and field equipment, as well as of all infrastructure assets, were as those observed in the retail market in December 2014. These were described and inventoried for all areas of the rural establishments and calculated as a proportion to the planted areas. Subsequently, the technical itineraries of coconut crop management were defined, including all stages of cultivation, input types and amounts used, prices paid for inputs, operating costs of machinery and implements, as well as manual labor required for each operation. Production costs were determined based on the effective operational cost (EOC) with the use of manual labor, machinery/equipment, vehicles and materials, and total operating cost (TOC) resulting from EOC plus depreciation for machinery and equipment, other expenses (5% of EOC) and financial charges (incident interest rates, considering 6% to 50% of EOC). Profitability indicators used in the study were based on the work of Sabbag and Nicodemo (2011).

For the current study, six reference farms dedicated to coconut production and partners with Embrapa in technology development and transfer programs were selected to carry out case studies. Farms were selected among mainstream coconut commercial operations, all considered innovative among their peers, and supported primarily by their agricultural production (as proposed in Firbank et al., 2013). These reference farms showed different levels of intensification and diversification, varied technology adoption capacities, and entrepreneurial strategies from family businesses to large-scale enterprises (Table 1). Field data surveys took place between July 2013 and November 2014, and results from each case study were reported back to the farm managers in 'Environmental Management Reports', containing all analytical results, documentation on environmental, social and

**Table 2**  
Analytic results and associated utility values for the water quality indicators determined for the six coconut production reference farms. Data from the APOIA-NovoRural impact assessment system.

Rural establishment	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Indicators (units)	Parameter value	Utility value	Parameter value	Utility value	Parameter value	Utility value
Dissolved oxygen (mg L <sup>-1</sup> )	2.27	0.42	7.6	0.81	4.87	0.72
Thermotolerant coliforms (CFU 100 ml <sup>-1</sup> )	0.0	1.0	0.0	1.0	0.0	1.0
pH (acidity induction)	5.6 ⇒ 4.9	0.61	7.33 ⇒ 7.25	0.39	6.9 ⇒ 6.9	0.99
Nitrate (mg L <sup>-1</sup> )	2.5	1.0	5.0	0.98	2.5	1.0
Phosphate (mg L <sup>-1</sup> )	nd	nd	nd	nd	0.1	0.89
Turbidity (TNU)	5.0	0.98	0.4	1.0	1.2	1.0
Chlorophyll (µg L <sup>-1</sup> )	nd	nd	nd	nd	nd	1.0
Conductivity (mS cm <sup>-1</sup> )	0.18	0.95	0.13	0.95	0.608	0.95
Visual water pollution (period of occurrence)	100% no occur.	1.0	100% no occur.	1.0	100% no occur.	1.0
Potential pesticide impact (% area)	Unaltered 100% area	0.70	Freq. and Tox. reduction 100% area, active ingred. Reduction 70% area	0.74	Freq. and Tox. reduction 1% area, no use 99% area	Freq. increased/Tox. reduction 20% area
Thermotolerant coliforms in groundwater (CFU 100 ml <sup>-1</sup> )	0.0	1.0	0.0	nd	0.0	1.0
Nitrate in groundwater (mg L <sup>-1</sup> )	5.0	0.99	2.5	nd	18.0	1.0
Conductivity in groundwater (mS cm <sup>-1</sup> )	0.216	0.95	nd	nd	0.503	0.95
Average Water Quality Index		0.87		0.86		0.94

**Table 3**  
Analytic results and associated utility values for the soil quality indicators determined for the six coconut production reference farms. Data from the APOJA-NovoRural impact assessment system.

Rural establishment	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6	
	Parameter value	Utility value	Parameter value	Utility value	Parameter value	Utility value	Parameter value	Utility value	Parameter value	Utility value	Parameter value	Utility value
Indicators (units)												
Organic matter buildup (%)	0.8 ⇒ 0.8	0.70	1.14 ⇒ 0.82	0.31	1.0 ⇒ 1.7	0.99	1.3 ⇒ 1.2	0.99	0.8 ⇒ 0.8	0.60	1.8 ⇒ 2.3	0.70
pH (acidity induction)	5.2 ⇒ 5.2	0.99	5.6 ⇒ 6.7	0.99	6.8 ⇒ 7.0	0.99	5.2 ⇒ 5.3	0.99	6.0 ⇒ 6.0	0.99	4.1 ⇒ 4.6	0.99
Phosphate (mg dm <sup>-3</sup> )	15.0	0.40	17.1	0.45	380	0.10	25	0.10	18.3	0.60	6.4	0.21
Exchangeable K (mmolc dm <sup>-3</sup> )	0.80	0.24	1.56	0.41	1.6	0.42	1.2	0.42	1.0	0.34	0.5	0.17
Exchangeable Ca (mmolc dm <sup>-3</sup> )	10.0	-	14.5	-	20.0	-	15	-	7.0	-	12.6	-
Exchangeable Mg (mmolc dm <sup>-3</sup> )	3.0	0.55	7.0	0.92	6.0	0.86	3.0	0.86	4.0	0.55	1.9	0.67
H + Al (mmolc dm <sup>-3</sup> )	9.0	0.91	3.5	0.91	10.0	0.76	12.0	0.76	8.0	0.72	36.0	0.81
Sum of bases (mmolc dm <sup>-3</sup> )	13.8	0.18	23.1	0.50	27.6	0.63	19.2	0.63	12.0	0.38	15.0	0.13
Cation exchange capacity (mmolc dm <sup>-3</sup> )	22.8	0.49	26.6	0.60	37.6	0.80	31.2	0.80	20.0	0.70	51.0	0.40
Bases saturation (%)	60.5	0.53	86.8	0.84	73.4	0.68	61.5	0.68	60.0	0.54	29.4	0.53
Erosion (% area)	Unaltered laminar in 100% area	0.70	Unaltered laminar in 100% area	0.70	Unaltered laminar in 100% area	0.70	Reduced laminar in 100% area	0.70	Reduced laminar in 100% area	0.82	Unaltered laminar in 100% area	0.82
Average Soil Quality Index		0.57		0.66		0.69		0.62		0.62		0.58

economic performances, and recommendations toward improving the sustainability of the farming systems.

Contrasting levels of diversification and technology adoption in the six reference farms warranted a broad gradient of intensification levels and adoption of ecologically intensive practices. Cases 1 and 3 applied basically conventional farming practices, while case studies 2, 4, 5 and 6 adopted different levels of ecologically based management, including coconut phenotyping and genetic improvement, crop diversification, organic fertilization, legume cover crops, tilling and mowing for weed control, animal traction, mulching, biological insect control/integrated pest management and coconut-dairy integrated systems (Table 1). As a consequence, these establishments reached increasing levels of autonomy, breadth of commercial ties, certification strategies and levels of market insertion.

### 3. Results

#### 3.1. Environmental performance and ecological intensification analyses

The environmental performances observed in the studied farms, as defined by the average indices of the 62 indicators of the APOJA-NovoRural impact assessment system were 0.71 for Case1, 0.79 for Case 2, 0.75 for Case 3, 0.8 for Cases 4 and 5 and 0.79 for Case 6, and showed an average of 0.78 for the integrated multi-attribute utility indices. In general, all sustainability dimensions scored above the compliance baseline, except for constraints in soil fertility, in all farms (Fig. 1). Environmental performance magnitudes were primarily determined by the indicators of Water quality, followed by Economic values and Management & administration, as detailed in the following subsections.

#### 3.2. Landscape ecology dimension

The set of indicators of the Landscape ecology dimension (average index = 0.73) helped to record the rigorous attention to the natural habitats status in the studied establishments, especially in reference to the precepts of the Brazilian Forest Code, namely the Legal Preserve and the Permanent Preservation Areas, which have been kept free of the access of domestic animals, fire or other impacts (Fig. 2). Adequate indices were observed for the productive areas management and animal husbandry/confined activities, in those establishments were livestock integration occurred. Despite these environmental qualities, moderate performance indices resulted to indicators such as ecological corridors, degraded areas reclamation, and incidence of endemic disease vectors, due to lack of impact in these aspects (no change = 0.7).

On the other hand, landscape and productive diversities were mostly low, given the preponderance of coconut monoculture among the productive activities (except Cases 2 and 5, see Table 1). Strictly speaking, these results represent a methodological bias, because emphasis is placed on the variety of landscapes (gamma diversity), not in species richness (alpha diversity), which in turn is often quite high, as evidenced by the excellent performance in the indicator related to prevention of species extinction risk (Fig. 2), that considers ecologically relevant wildlife.

Moreover, the low productive diversity is a strategic decision in the majority of the studied farms, specialized in coconut production, even when directed to varied end products, such as tender coconut water and coconut milk and meat. Also in this dimension, fire risks have been minimized, as compared with other land uses, through the maintenance of firebreaks, care in the distribution of stubbles and straw, and management of the coconut plantation understory, including soil cover with kudzu (*Pueraria* sp., which increases humidity), besides the maintenance of fire brigades in the farms. With regard to geotechnical risks, drainage measures have helped to reduce flooding in certain areas.

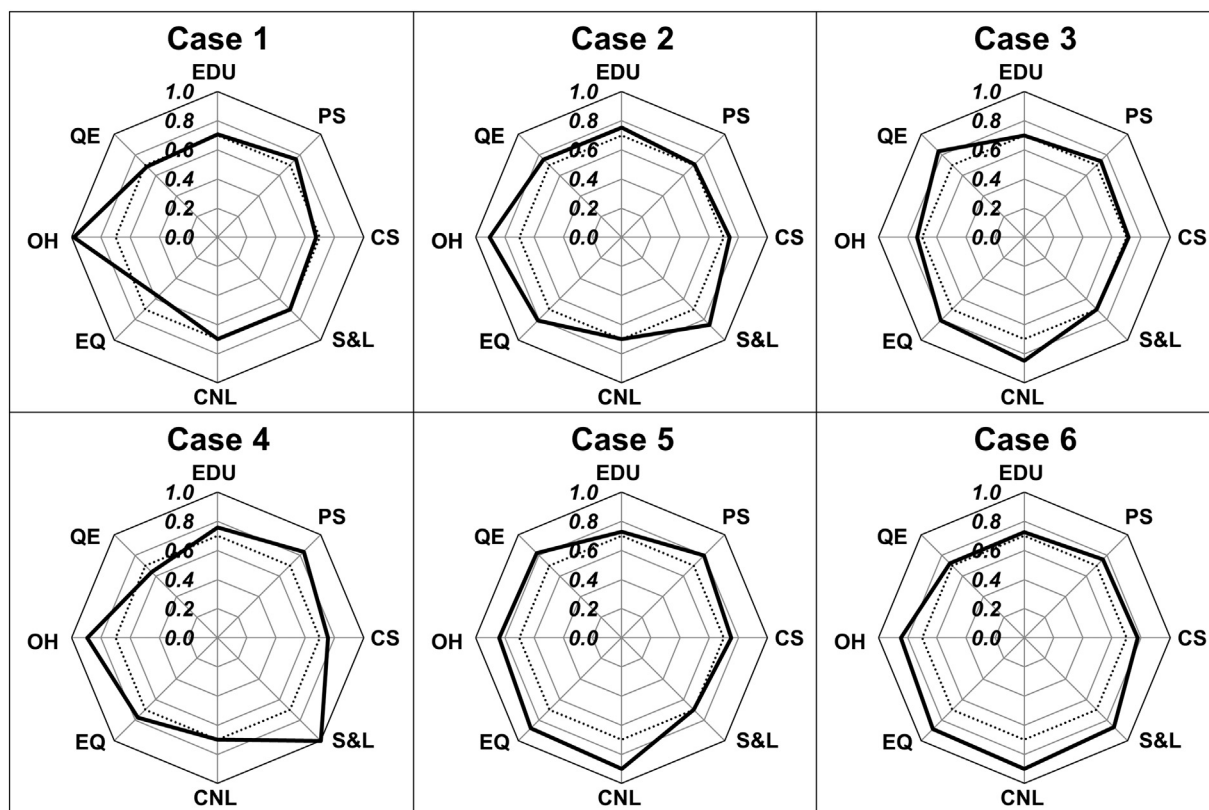


Fig. 4. Results for the Sociocultural values sustainability dimension, for the six studied rural establishments dedicated to coconut production. Data from the APOIA-NovoRural impact assessment system. The dotted lines represent the 0.7 baseline compliance level. Indicators: EDU: Education; PS: Public services; CS: Consumption standards; S&L: Sports and leisure; CNL: Cultural/Natural legacy; EQ: Employment quality; OH: Occupational health; QE: Qualified employment.

### 3.3. Environmental quality dimension

The Environmental quality indicators (average index for the three compartments, atmosphere, water and soil = 0.78) pointed out virtual absence of impacts to the atmosphere, as emissions from fossil fuels, which are related primarily with input applications and harvesting, tend to be rationalized due to high costs. Especially favorable performance was estimated for Case 06, both in relation to  $\text{CO}_x$  and  $\text{NO}_x$  emissions (Fig. 3), as a result of traction animals being used in harvesting (reducing  $\text{CO}_x$  emissions); and a well-established adventitious plants management system, coupled with kudzu maintenance as primary nitrogen fertilization strategy (reducing  $\text{NO}_x$  emissions).

Higher levels of  $\text{NO}_x$  emissions were estimated for Case 5 (resulting in lower performance) as a result of integration with animal husbandry (dairy cows), and the application of stabilized liquid manure through a continuous fertigation system, also associated with some local generation of odor (Fig. 3). In general terms, environmental performances related to the atmosphere compartment were quite favorable (average index = 0.83 – Fig. 1), also as a consequence of some of the Landscape ecology indicators, such as fire prevention and natural habitats conservation status.

Still linked to the Environmental quality sustainability dimension, water quality indicators proved to be excellent in all studied establishments (average index = 0.92), with almost every indicator showing performance indices well above the recommended values for Class II surface waters, as prescribed in the national water quality standards. Only exceptions were increased acidity observed in Cases 1 and 3; lower levels of oxygen in Case 1, which reference samples were obtained in a still reservoir of the irrigation system; and higher levels of phosphates in Case 4, related to a pond built to collect rainwaters from the surrounding plantations, also for irrigation purposes.

Analytic data on the 13 water quality indicators determined (three

for groundwater) and associated utility values are shown in Table 2. Among the noteworthy results are the high levels of oxygenation observed in the surface water bodies, hence characterized as oligotrophic reservoirs, ponds or streams with low levels of nutrients (N and P) and dissolved solids (low conductivity), low turbidity and chlorophyll contents, and virtual absence of detection of thermotolerant coliforms, even for the coconut-livestock integrated system (Case 5), which samples were obtained in a natural lake, away from the pastures and milking premises.

This result attests to the efficiency of the liquid manure pretreatment and fertigation system employed in this farm, where, on the other hand, higher levels of nitrates were measured in the groundwater, indicating nutrient percolation through the soil. Also absent in all cases were signs of waste disposal or visual pollution, whereas sensible pesticide usage patterns in all establishments contributed to improvements in potential impact indices. In this sense, substitution of active ingredients by less toxic products was carried out in all farms (especially crude cottonseed oil for mite control, see details ahead), even those where conventional plantation management was exercised.

Finally, in the Environmental quality dimension, Table 3 presents the analytic results for the 11 indicators of soil quality and associated utility values, as determined by the correspondence functions built in the APOIA-NovoRural impact assessment system. The modest levels of soil fertility in all establishments (average index = 0.61) pointed out the need for adjustments and parsimony in the application of fertilizers, as to avoid excesses that result in financial waste (as for phosphate in Case 3), water contamination (as for nitrate in Case 5) and eutrophication risks (due to both nutrients). In any case, soil management must seek to increase the supply of organic matter (decreased in Cases 2 and 4), in order to correct natural deficiencies and improve nutrient and water retention capacity in the soils, in general very sandy.

As can be observed in Table 3, soil management strategies have

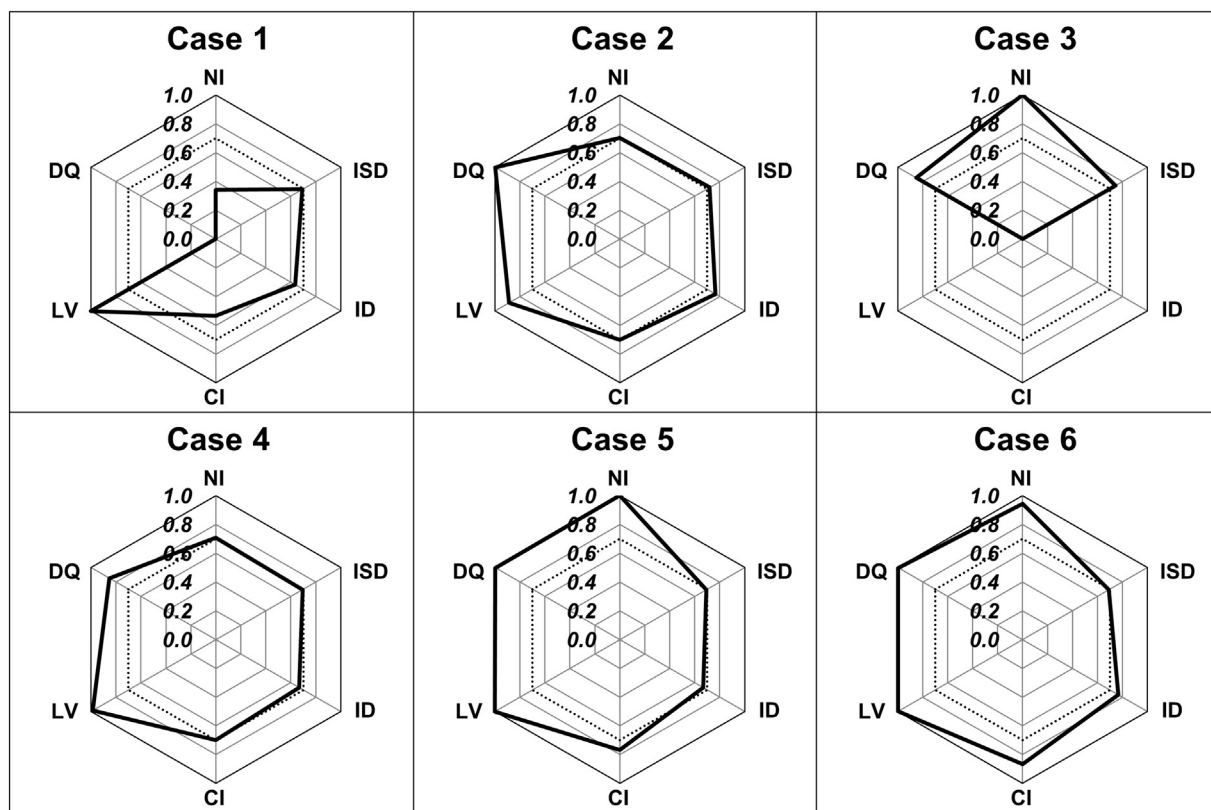


Fig. 5. Results for the Economic values sustainability dimension, for the six studied rural establishments dedicated to coconut production. Data from the APOIA-NovoRural impact assessment system. The dotted lines represent the 0.7 baseline compliance level. Indicators: NI: Net income; ISD: Income source diversity; ID: Income distribution; CI: Current indebtedness; LV: Land value; DQ: Dwelling quality.

sought to reduce soil acidity, which remains below pH 6.0 in three of the farms (Cases 1, 4 and 6), explaining the lower levels of bases saturation in these cases. Even if modest, levels of phosphate were considered satisfactory for coconut production (between 15 and 25 mg dm<sup>-3</sup>, with utility values ranging from 0.4 to 0.6), except for the exceedingly high levels for Case 3 (380 mg dm<sup>-3</sup>, much above plant needs, resulting in lower utility value 0.10); and insufficient for Case 6 (6.4 mg dm<sup>-3</sup>, utility value 0.21), under the more acidic, leached soils of this tropical rainforest Amazonian region. This specific situation of excess P detected in Case 3 caused a radical change in management, with exclusion of P from fertilizer formulation and financial savings in the order of US\$ 224 ha<sup>-1</sup> including application, or an estimated US\$ 31,584 annual economy for the 141 ha plantation. This represents 4.4% reduction in total production costs of dwarf coconut in a density of 205 plants ha<sup>-1</sup>, or 44 tons of simple superphosphate (18% P<sub>2</sub>O<sub>5</sub>), an important reduction in the ecological footprint of the farm (Skowrońska and Filipek, 2014).

Exchangeable potassium was low in all cases, resulting in low to very low sum of bases; while magnesium showed quite variable levels, with important implications on productivity, as explained ahead in the section on 'Integrated economic and environmental performances analyses'. Potential acidity and aluminum levels were mostly corrected, thus resulting in adequate cation exchange capacities (utility values between 0.40 e 0.80), except for the high acidity observed in Case 6 (H + Al = 36.0 mmolc dm<sup>-3</sup>, utility value = 0.33), making the high CTC in this farm (51 mmolc dm<sup>-3</sup>, utility value = 0.90) a result of the elevated soil organic matter content (23.0 g dm<sup>-3</sup>). The resulting low bases saturation (29.4%) in this case prompted the recommendation of liming application, as to promote high effect on production with relatively low cost and environmental impact. Erosion was well controlled in all farms, due to the high water infiltration capacity of the sandy soils, the flat landforms of most plantations, and the understory

management with wild vegetation or kudzu.

### 3.4. Sociocultural values dimension

With respect to the Sociocultural values dimension (average index = 0.78, Fig. 4), performance indices proved to be adequate for the whole set of indicators, with the exception of the employment quality indicator in Case 1, which was caused by overwork demanded from the farm manager, during the period encompassed by data collection. Several indicators remained unaltered by the management practices and provisions related with coconut farming, such as education and training, access to public services and consumption standards. Others tended to be favored by such provisions, such as occupational health, conservation of cultural legacy and qualified employment. These results imply a favorable inclination in all studied farms toward fulfillment of the needs of the personnel and their resident families.

### 3.5. Economic values dimension

The Economic values indicators (average index = 0.80) pointed out significant progress in all profitability attributes, reduced indebtedness, improved income distribution and exceptional gains in the property values, reflecting investments in productive assets, enhancement of the current market demand, and worth of coconut-derived products. An interesting common attribute of all studied farms was the quality of existing dwellings, be those available to employees or those for managers.

A notable exception to the excellent economic indicators observed in most farms was Case 1 (see Fig. 1), result of a transient situation caused by a long-lasting and severe drought present at the time of data collection. This situation imposed a depression in net income, due to diminished productivity, and the need for investments in new wells to

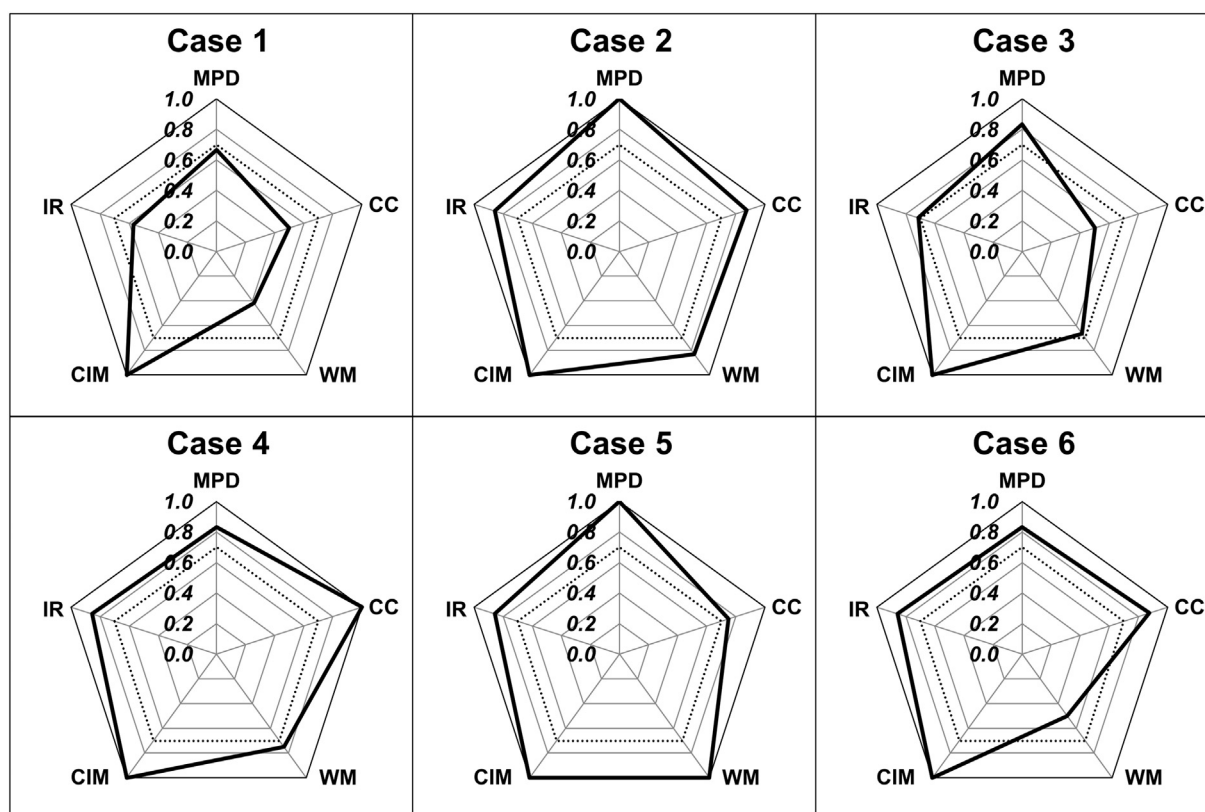


Fig. 6. Results for the Management and administration sustainability dimension, for the six studied rural establishments dedicated to coconut production. Data from the APOIA-NovoRural impact assessment system. The dotted lines represent the 0.7 baseline compliance level. Indicators: MPD: Manager profile and dedication; CC: Conditions of commercialization; WM: Waste management; CIM: Chemical inputs management; IR: Institutional relationship.

Table 4

Financial performances of the annual production of coconut in different rural establishments and production systems in Brazil.

Item	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Mean
Yield (coconuts.ha <sup>-1</sup> )	26000	36900	40710	17160	33496	19200	28911
Selling price (US \$.coconut <sup>-1</sup> )	0.44	0.33	0.34	0.44	0.26	0.36	0.36
Gross revenue (US \$.ha <sup>-1</sup> )	11420	12318	13769	7537	8681	8433	10360
Operating cost (US \$.ha <sup>-1</sup> )	3108	4862	8406	5244	5925	2910	5076
Inputs	1558	1839	2413	1245	2302	1050	1822
Manual operations	795	1222	3973	2772	2148	1173	1924
Mechanized operations	755	1800	2020	1227	1475	687	1330
Benefits/Costs <sup>a</sup>	3.6	1.7	2.6	1.5	1.5	3.0	2.3

<sup>a</sup> Benefits/Costs = Gross revenue/Operating Costs.

warrant irrigation, causing temporary debt. This farm had no residents, reason for the lacking dwelling quality indicator (Fig. 5).

An interesting contrast was observed for the farming systems represented by Cases 1 and 3. Although being quite similar regarding intensification levels and technology adoption aspects (conventional coconut monoculture, see Table 1), the mean utility values for the Economic indices in Case 3 were substantially higher than Case 1 (0.87 against 0.64, respectively – Fig. 1). The main difference between these two cases was the management type. While Case 1 corresponds to a family business, the farm represented by Case 3 belongs to a solid corporation, with money-backing capacity to support periods of environmental or market constraints. This result supports the premise that crop diversification is an essential ecological intensification measure to

ensure financial security, especially to family run rural establishments.

### 3.6. Management and administration dimension

Finally, the performance in the Management and administration sustainability dimension (average index = 0.82, Fig. 6) showed quite variable technical proficiencies of the farmers (or management teams), as expressed in the manager profile and dedication indicator. Quite interestingly, this indicator revealed a close association with the general performance in this dimension, i.e., the better the qualification and professional proficiencies of the managers, the better the performances, e.g., in the conditions of commercialization, waste disposal practices and institutional relationships. The chemical inputs management indicator depicted full compliance, in all studied farms.

### 3.7. Profitability and economic viability analysis

Results of the economic performances for the six coconut farming systems studied are shown in Table 4. On the average, manual operations were the factors that interfered most with effective operational costs, accounting to 38%, followed by the cost of inputs with 36%, and mechanized operations with 26%. In the family-run establishments (Cases 1, 2 and 5) greater participation in operating costs were related to inputs, while in the business-type establishments the manual operations were those requiring more financial resources.

In relation to production costs, it is noteworthy that the control of the coconut-necrosis-mite (*Aceria guerreronis*) demanded major economic efforts. Only with the control of this pest 14–20 interventions are required annually. Although crude cottonseed oil, a low toxicity product, has been the main alternative used for controlling this pest, agrochemical applications accounted for over 40% of the total coconut production costs, when the mechanized operations required to

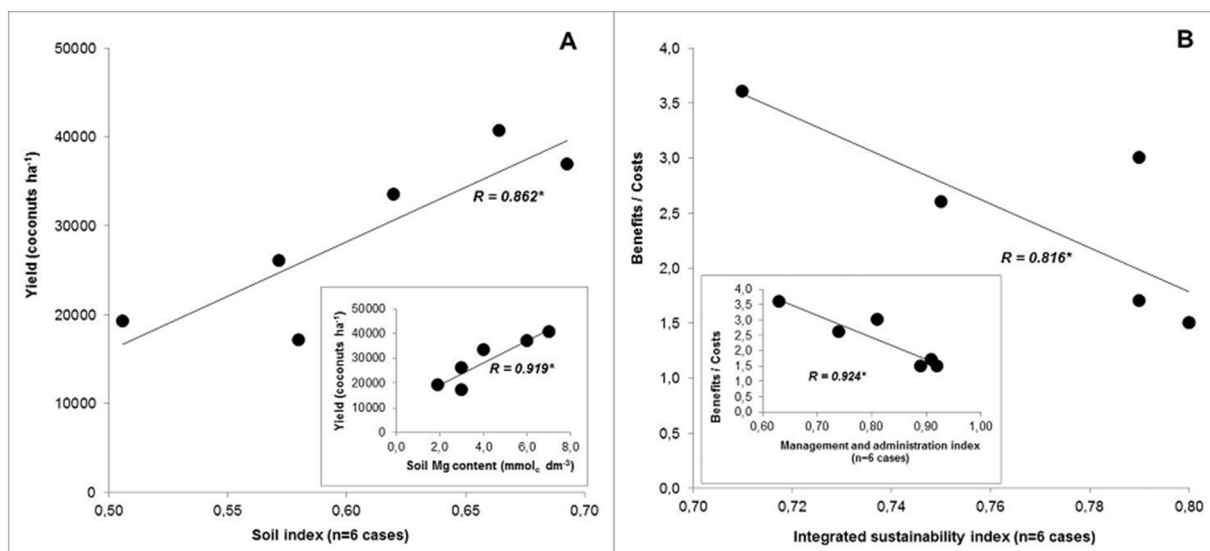


Fig. 7. (A) Yield responses of coconuts to soil quality indices and soil Mg content. (B) Correlation between Benefits/Costs and the integrated sustainability and the Management and administration dimension indices in six case studies in Brazil. \* indicates that the correlation is significant by Student *t*-test at  $p < 0.05$ .

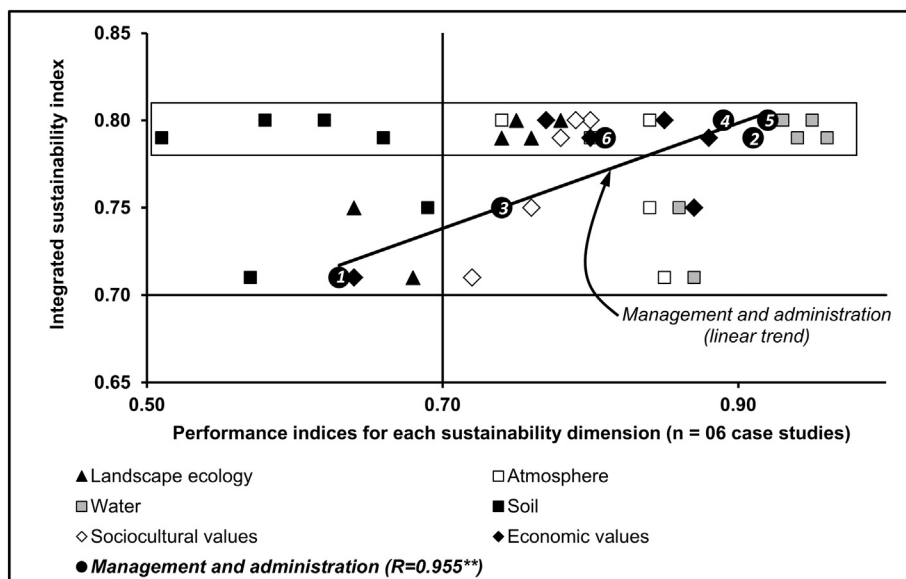


Fig. 8. Results of environmental indicator analyses in reference to coconut production farms. The four rural establishments characterized as ‘ecologically intensive’ are highlighted (frame), and case studies are identified for the Management and administration dimension. \*\* indicates that the correlation is significant by the Student *t*-test at  $p < 0.01$ .

implementing these practices were included. These represent a major technical factor to be overcome in terms of ecological intensification, given the strong influence on production and profitability.

The yield and revenue parameters associated with annual production of coconut in the different production systems studied showed that, with the exception of Case 1, farms with dwarf coconut plantations (Cases 2, 3 and 5) were within expected productivity ranges, while Cases 4 and 6 showed productivities near the expected for hybrid varieties. For these yield ranges and financial conditions the profits of all systems showed adequate economic viability, with benefit/cost ratios between 1.5 and 3.6, attesting to the potential of this culture in economic terms.

Different to cash crops, that usually show small price variations between locations, the price of coconut at farm gate vary greatly depending on the region where it is produced. This variation was detected in this study, since the range in selling prices was from US\$0.26 to US\$0.44 per nut, and the main factors influencing this variation were the distance from the market, the use or not of commercial intermediaries and the destination of the production, either for consumption “in

natura” or industrial use.

### 3.8. Integrated economic and environmental performances analysis

Even though the aggregated index for soil quality indicators was below sustainability baseline in all cases studied, coconut yields were responsive to soil quality, as shown in Fig. 7A in the context of this study. For instance, magnesium contents correlated significantly with yield even in the restricted sampling size. In general, soil Mg contents below 4 mmol<sub>c</sub> dm<sup>-3</sup> are considered too low to support yields, since coconuts are especially demanding for this nutrient. In the average of all studied cases, the soil quality index was 0.61 (varying from 0.51 to 0.69) attesting to the low soil quality normally observed in coconut producing areas in Brazil, generally sandy soils with low ion holding capacity and, as a consequence, low capacity to supply nutrients.

The distribution of performance indices for the different sustainability dimensions can be seen in Fig. 8 relative to the integrated sustainability indices obtained for all reference farms studied. One can observe that all farming systems scored above the baseline for the

integrated sustainability indices, while the ample spread of results in the abscissa depicts the contrast between the lower soil quality, as compared with the excellent water quality indices observed in all farms. The four reference cases characterized as ecologically intensive farming systems (Cases 2, 4, 5 and 6, Table 1), due to the adoption of several improved management practices and technologies, are highlighted in the frame.

## 4. Discussion

### 4.1. Integrated pest management practices

The coconut-mite causes severe losses in producing countries of Africa, Asia and the Americas (Navia et al., 2013; Negloh et al., 2008), and it is by far the most important nuisance in Brazil and overall in the Northeast, due to favorable climatic conditions (Rezende et al., 2016). Control is difficult due to its habit of feeding and reproducing under the fruit bracts, protected from pesticide sprays (Souza et al., 2012). Although dependent on frequent pest control interventions to warrant good yields, especially against the coconut-mite, all establishments predominantly spray cottonseed oil as an effective control measure, which represents an important benefit, both economic and environmental. The use of this product represents a breakthrough in the control of this particular pest, in terms of lower effects on natural enemies (Oliveira et al., 2017), absence of risk to workers and improved food safety (Teodoro et al., 2017). Additional cultural practices must be observed, as to reduce costs and improve the effectiveness of mite control, e.g., removal of damaged fruits from the orchards, their incineration or burial to prevent spread to other fruit, and release of natural enemies to promote biological control (Fernando et al., 2010). These practices should be a priority, as the coconut-necrosis-mite causes losses in fruit size and weight, and reduction in commercial value (Rezende et al., 2016).

It is worth noting that in this study 14 to 20 phytosanitary interventions were observed just for the control of this pest, meaning that when inputs, machinery and labor force for application are accounted for, it becomes evident the importance of adopting adequate technical solutions in terms of ecological intensification, in order to overcome the impacts on production costs and profitability.

In many coconut producing countries, especially in Asia, Africa and the Caribbean, some other pests like coconut black-headed caterpillar (*Opisina arenosella*), red palm weevil (*Rhynchophorus ferrugineus*) and Asiatic rhinoceros beetle (*Oryctes rhinoceros*) are also very noxious to coconut. However, their presences in continental South America are not yet reported.

### 4.2. Soil management practices

Main recommendations included in the environmental management reports issued to farmers concerned adjustments and parsimony in the application of fertilizers, as to avoid excesses that result in financial losses (case of phosphorus) and water contamination risks (case of nitrogen). Also, increase in the supply of organic matter, to correct natural deficiencies and improve nutrient and water holding capacity, in the naturally very sandy soils. In any case, considering that fertile soils should be dedicated to staple food production in order to promote sustainability, coconut cultivation in such marginal areas might be deemed in line with the principles of ecological intensification. In general, the other indicators related to the Environmental quality dimension were adequate in the studied farms, such as compliance with landscape management requirements, excellent water quality and lack of noticeable atmospheric emissions.

### 4.3. Indicators trade-offs and communication for decision-making

Farm case studies often show that sustainability dimensions may

exhibit either subordinate or independent relationships according to specific contexts and management objectives. Sometimes, good economic performances positively correlate with adequate environmental conservation, promoting synergies in the aggregated sustainability indices, while in the opposite direction components of economic savings, e.g., in wage payments, may compromise social performances, generating compensation among dimensions (Ripoll-Bosch et al., 2012) and trade-offs within farms or across assessment scales (farm, local community, or region) (Gathorne-Hardy et al., 2016).

A scatter plot regression tradeoff analysis between economic and integrated sustainability indices showed that benefit/cost ratios declined as sustainability increased (Fig. 7B). This was so because higher sustainability indices were obtained in farming systems with improved share of income distribution among stakeholders, investment in training, provision of quality working conditions and benefits for laborers (protection equipment, health insurance, productivity bonuses, annual paid leave, etc), promotion of recreational and cultural activities and attention to the workers' quality of life (i.e., indicators in the socio-cultural values dimension).

All these aspects demanded both additional costs and, therefore, reduction in operational profits, and a higher degree of organization. Hence a reduction in benefit/cost ratios (limited to a level that would not threaten the enterprises' own existence) is expected as sustainability increases. Nevertheless, the lowest benefit/cost ratio among all cases studied was 1.5 (Table 4), indicating that significant social benefits can be achieved along with adequate economic sustainability status in coconut production, following the principles of ecological intensification.

Agreeing with observations previously reported by Rodrigues et al. (2010), a highly significant correlation was observed between the performance indices for the management and administration dimension and the integrated sustainability indices obtained for all farming systems studied (trend line in Fig. 8). This important decision making correlation was again observed in the present work, despite the limited number of cases studies. This result corroborates the hypothesis that sustainable agricultural systems tend to be favored by the adoption of environmental management systems, as decision support tools to draw strategies regarding the monitoring and organization of rural establishments, including the ones dedicated to coconut production.

Hence, it is crucial that sustainability assessment tools facilitate (or provide clear indications to) the handling of conflicts between the different dimensions and indicators (Kanter et al., 2016). A particularly troublesome consequence of such apparent inconsistencies in the interpretation of the assessments is a recurrent difficulty for clearly communicating results to stakeholders (Slätmo et al., 2017), in a manner that incite them to take practical action. In this sense, de Olde et al. (2018) identified a 'remarkable absence of reflective discussions, especially in relation to how the results [of sustainability assessments] can influence agriculture in practice'.

The difficulty for clearly communicating assessment results to elicit the handling of trade-offs, as to correct management and implement indicators' results in practice, is a general lack of critical scrutiny in indicator interpretation – a tendency to emphasize optimistic pictures, while negative (or detrimental) issues observed in the assessments can be effectively masked (Slätmo et al., 2017). Conversely, our approach primarily highlights such detrimental issues, stressing in the environmental management reports issued to farmers the very trade-offs and performance faults found, and the respective recommendations for corrective actions.

From this standpoint, performance indices become a yardstick of changes to pursue, or of deficiencies to accommodate, submitted to farmers' choices and discernment with respect to their specific productive contexts. As such, the assessment tool – and the associated indicator-based benchmarks – represents a true decision-making aid, rather than an expression of power of the developers or technical experts performing the analysis (Gasparatos, 2010).

#### 4.4. Implementation of changes

According to Bezlepikina et al. (2011), there are three essential aspects to be covered, or issues to pursue in integrated sustainability assessments, aiming at the effective implementation of changes in agricultural practices: (i) The relevant sustainability dimensions, in our case involving the three-pillar-approach (environmental, economic and social), represented in the five aggregate dimensions studied; (ii) The integration of assessment scales, in our case (a) the cropping fields, with analytic instrumentation and surveys; (b) the whole farms, with the decision-making model application and the ensuing farm environmental management reports; and (c) the productive sector, with the economic benchmarks for coconut production; and (iii) The stakeholder involvement, which occurred directly in our study, be as expert informants, critical reviewers of procedures and results, and presenters of peers, for completing the sample of reference farms of the study.

Once resolved under these premises, the results of the sustainability assessments carried out prompted many instances of implementation and effective changes among the rural establishments involved in the research, such as the exclusion of phosphate from the fertilization program in Case 3, and the Rainforest Alliance certification of Case 4, based on the environmental management report resulting from the study.

In this sense, the decision-making capacity of the farmers/farm managers showed to be the main determinant of changes, following their critical analysis of feasibility regarding each recommendation issued from the indicators' results, as presented to them and discussed in the environmental management reports. Once again, and even if subjected to a restricted sample (six reference cases), a close correlation was observed between results of the Management and administration dimension and integrated sustainability indices for all farms. This result closely matches the observations of Rodrigues et al. (2010), supporting the hypothesis according to which the sustainability of rural activities in general, as well as coconut production in particular, can be widely favored by the adoption of environmental management tools, such as the APOIA-NovoRural indicators system.

#### 5. Conclusions

The results obtained in this study favored the identification of appropriate mechanisms of intensification, related with agronomic factors and practices adopted in the production process, which interfere positively with economic and environmental performance indicators. The farming systems adopted in all establishments resulted in higher revenues than costs, demonstrating economic viability in coconut production. The most significant components in the composition of costs were manual operations and inputs, such as fertilizers and especially miticides/insecticides, indicating the value of ecological intensification technologies that allow reduction in production costs and improvement in profitability, worker safety, and environmental balance.

Socio-cultural values indicators were all favorable, given the provision of training to employees, very good employment and benefit conditions, and access to basic services. The Management and administration dimension proved to be closely dependent on the entrepreneurial and productive contexts of the studied establishments, both for those dedicated to coconut monocultures as well as the diversified ones.

Despite observed trade-offs on economic indicators that usually precede other dimensions, the indicators of socio-cultural values held significance in determining sustainability, strengthening the multidimensional aspect of ecological intensification. By the same token, the environmental performances of the rural establishments dedicated to coconut production were much improved when the productive contexts were more diversified and integrated, attesting to the value of technology adoption and ecological intensification as strategies to improve sustainability.

All these interactions among indicators interpreted in the proposed sustainability assessment, and the ensuing recommendations issued to farmers and management teams, correspond to strides in translating farm-level sustainability assessments into action for sustainable development.

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