

ABSTRAK

PENGEMBANGAN MODEL RESPIRASI TANAH DI LINGKUNGAN PERKEBUNAN NANAS: KONTRIBUSI BAGI AKUNTANSI GRK MENUNJANG IMPLEMENTASI PERDAGANGAN KARBON SEKTOR PERTANIAN

**Oleh:
Imron**

Respirasi tanah merupakan salah satu komponen utama fluks karbon dioksida (CO_2) dari sistem pertanian ke atmosfer dan berkontribusi signifikan terhadap emisi gas rumah kaca (GRK), khususnya di wilayah tropis. Pada perkebunan nanas, praktik pengelolaan tanah yang intensif berpotensi mengubah kondisi fisik-kimia tanah dan aktivitas biologis tanah, yang pada akhirnya memengaruhi besarnya respirasi tanah. Namun, pendekatan akuntansi GRK di sektor pertanian masih didominasi oleh pendekatan berbasis praktik dan input, tanpa pemahaman yang memadai mengenai mekanisme proses yang menghubungkan pengelolaan tanah dengan emisi karbon tanah. Kebaruan penelitian ini terletak pada pengembangan model respirasi tanah berbasis proses melalui pendekatan empiris berjenjang yang memisahkan secara eksplisit jalur kausal antara *soil management*, *soil properties*, *soil biota*, dan *soil respiration*. Pendekatan ini memungkinkan identifikasi pengendali langsung dan tidak langsung respirasi tanah, sehingga memperkuat dasar ilmiah akuntansi GRK berbasis proses dan mendukung kredibilitas implementasi perdagangan karbon di sektor pertanian. Urgensi penelitian ini semakin meningkat mengingat kebutuhan akan indikator biologis tanah yang terukur dan sensitif dalam sistem *Measurement, Reporting, and Verification* (MRV) karbon pertanian tropis. Penelitian ini bertujuan untuk: (1) Menetapkan sensitivitas parameter dari *soil tillage* dan *soil amelioran* (compost, biochar, Vermist dan mikroorganism) terhadap *soil properties* (temperatur, kadar air, pH); (2) Menetapkan Sensitivitas parameter *soil properties* terhadap *soil biota improvement*; (3) Merancang persamaan simultan respirasi tanah sebagai fungsi dari *soil biota* dan *soil biota* sebagai fungsi dari *Soil properties* yang merupakan fungsi dari *Soil Management*. Metode penelitian menggunakan pendekatan kuantitatif dengan model regresi linier berjenjang (*recursive regression models*) yang terdiri atas tiga kelompok model. Model I [A,B,C] menganalisis pengaruh *soil management* terhadap pH tanah, kadar air tanah, dan suhu tanah. Model II [A,B,C] menguji pengaruh *soil properties* terhadap mesofauna tanah, biomassa mikroba tanah (C-mik), dan cacing tanah. Model III menganalisis pengaruh biota

tanah terhadap respirasi tanah. Seluruh pengujian statistik dilakukan pada tingkat kepercayaan 90%.

Model IA menunjukkan (TIME) berpengaruh positif dan sangat signifikan terhadap pH tanah ($\alpha = 0,0057$; $p < 0,001$), artinya setiap kenaikan satu satuan waktu diikuti oleh peningkatan pH tanah sebesar 0,0057 unit. Penerapan vermikompos berasosiasi dengan peningkatan pH tanah sebesar 0,2057 unit ($p = 0,039$), sedangkan inokulan bakteri menunjukkan pengaruh yang lebih kuat dengan peningkatan pH tanah sekitar 0,25 unit ($p = 0,012$). **Model IB** (TIME) memiliki pengaruh negatif yang signifikan terhadap kadar air tanah ($\beta = -0,0327$; $p = 0,004$), yang menunjukkan penurunan kadar air tanah sebesar 0,0327 unit untuk setiap kenaikan satu satuan waktu. Perlakuan biochar menunjukkan pengaruh negatif terhadap kadar air tanah dengan koefisien sebesar $-1,6775$ ($p = 0,083$), yang mengindikasikan penurunan kadar air tanah sekitar 1,68 unit. Pengaruh serupa juga ditunjukkan oleh vermikompos, dengan koefisien $-1,6811$ ($p = 0,082$). **Model IC** menunjukkan TIME berpengaruh negatif dan sangat signifikan terhadap suhu tanah ($\lambda = -0,0163$; $p < 0,001$), kenaikan satu satuan waktu pengamatan diikuti oleh penurunan suhu tanah sebesar $0,0163$ °C, sedangkan vermikompos secara signifikan menurunkan suhu tanah dengan koefisien $-0,8333$ ($p = 0,039$), dan inokulan bakteri menunjukkan pengaruh yang lebih besar dengan penurunan suhu tanah sebesar $1,1111$ °C ($p = 0,012$). **Model IIA** menunjukkan bahwa suhu tanah berpengaruh positif dan signifikan terhadap kelimpahan mesofauna ($\alpha = 2,2600$; $p = 0,038$), yang berarti bahwa peningkatan suhu tanah diikuti oleh peningkatan mesofauna sebesar 2,26 unit. Kadar air tanah juga berpengaruh positif terhadap mesofauna ($\alpha = 0,5611$; $p = 0,050$). Sebaliknya, pH tanah menunjukkan pengaruh negatif yang signifikan ($\alpha = -6,5580$; $p = 0,040$), yang mengindikasikan bahwa peningkatan pH tanah diikuti oleh penurunan kelimpahan mesofauna. **Model IIB** suhu tanah berpengaruh positif signifikan terhadap (C_MICR) ($\beta = 0,4603$; $p = 0,034$) menunjukkan bahwa setiap kenaikan satu satuan suhu tanah diikuti oleh peningkatan biomassa mikroba sebesar 0,46 unit, pH tanah menunjukkan pengaruh positif yang sangat signifikan dengan koefisien sebesar $2,7805$ ($p < 0,001$), setiap kenaikan satu unit pH tanah diikuti oleh peningkatan biomassa mikroba tanah sebesar 2,78 unit. **Model IIC** pH tanah berpengaruh negatif signifikan terhadap populasi cacing tanah (E_WORM) ($\beta = -0,1204$; $p = 0,028$), yang berarti bahwa setiap kenaikan satu unit pH tanah diikuti oleh penurunan populasi cacing tanah sebesar 0,1204 unit. **Model III** biomassa mikroba tanah (C_MICR) menunjukkan pengaruh positif terhadap respirasi tanah (RESP) dengan koefisien sebesar 0,1692 pada tingkat kepercayaan 90% ($p = 0,075$) artinya setiap peningkatan satu unit biomassa mikroba tanah diikuti oleh peningkatan respirasi tanah sebesar 0,1692 unit. Hasil ini mengindikasikan bahwa peningkatan biomassa mikroba tanah berasosiasi dengan peningkatan respirasi tanah, sementara variabel biota tanah lainnya tidak menunjukkan pengaruh yang signifikan.

Secara keseluruhan, penelitian ini menegaskan bahwa respirasi tanah di perkebunan nanas dikendalikan terutama oleh komponen mikroba tanah, dan pengelolaan tanah memengaruhi emisi karbon secara tidak langsung melalui perubahan sifat fisik–kimia tanah dan respon biota tanah. Temuan ini memberikan kontribusi penting bagi pengembangan akuntansi GRK berbasis proses serta mendukung implementasi perdagangan karbon yang lebih kredibel dan berbasis ilmiah di sektor pertanian.

Kata Kunci: *biochar, carbon accounting, MRV, soil microbial biomass, soil management, soil property, soil biota, soil water content, tillage.*

ABSTRACT

DEVELOPMENT OF A SOIL RESPIRATION MODEL IN PINEAPPLE PLANTATION SYSTEMS: CONTRIBUTIONS TO GREENHOUSE GAS ACCOUNTING IN SUPPORT OF CARBON TRADING IMPLEMENTATION IN THE AGRICULTURAL SECTOR

**By:
Imron**

Soil respiration is one of the major components of carbon dioxide (CO₂) fluxes from agricultural systems to the atmosphere and contributes significantly to greenhouse gas (GHG) emissions, particularly in tropical regions. In pineapple plantations, intensive soil management practices have the potential to alter soil physicochemical conditions and biological activity, thereby influencing the magnitude of soil respiration. However, GHG accounting approaches in the agricultural sector are still predominantly based on management practices and input-oriented methods, with limited understanding of the process-based mechanisms linking soil management to soil carbon emissions. The novelty of this study lies in the development of a process-based soil respiration model using a hierarchical empirical approach that explicitly disentangles the causal pathways among soil management, soil properties, soil biota, and soil respiration. This approach enables the identification of both direct and indirect controls of soil respiration, thereby strengthening the scientific basis of process-based GHG accounting and enhancing the credibility of carbon trading implementation in the agricultural sector. The urgency of this research is further emphasized by the growing need for measurable and sensitive soil biological indicators within Measurement, Reporting, and Verification (MRV) systems for tropical agricultural carbon accounting.

This study aimed to: (1) determine the sensitivity of soil tillage and soil amelioration parameters (compost, biochar, vermicompost, and microorganisms) to soil properties (temperature, soil water content, and pH); (2) assess the sensitivity of soil properties to soil biota improvement; and (3) Designing a system of simultaneous equations in which soil respiration is modeled as a function of soil biota, and soil biota is modeled as a function of soil properties, which in turn are functions of soil management. The research employed a quantitative approach using recursive linear regression models comprising three

groups of models. Model I [A, B, C] analyzed the effects of soil management on soil pH, soil water content, and soil temperature. Model II [A, B, C] examined the effects of soil properties on soil mesofauna, soil microbial biomass (C-mic), and earthworms. Model III analyzed the effects of soil biota on soil respiration. All statistical tests were conducted at a 90% confidence level.

Model IA showed that time (TIME) had a positive and highly significant effect on soil pH ($\alpha = 0.0057$; $p < 0.001$), indicating that each one-unit increase in time was associated with an increase in soil pH of 0.0057 units. Vermicompost application was associated with an increase in soil pH of 0.2057 units ($p = 0.039$), while bacterial inoculation exhibited a stronger effect, increasing soil pH by approximately 0.25 units ($p = 0.012$). In Model IB, TIME had a significant negative effect on soil water content ($\beta = -0.0327$; $p = 0.004$), indicating a decrease of 0.0327 units in soil water content for each one-unit increase in time. Biochar application showed a negative effect on soil water content with a coefficient of -1.6775 ($p = 0.083$), corresponding to a reduction of approximately 1.68 units. A similar effect was observed for vermicompost, with a coefficient of -1.6811 ($p = 0.082$). Model IC indicated that TIME had a highly significant negative effect on soil temperature ($\lambda = -0.0163$; $p < 0.001$), meaning that each one-unit increase in observation time was associated with a decrease in soil temperature of 0.0163 °C. Vermicompost significantly reduced soil temperature by 0.8333 °C ($p = 0.039$), while bacterial inoculation resulted in a larger reduction of 1.1111 °C ($p = 0.012$).

Model IIA demonstrated that soil temperature had a positive and significant effect on mesofauna abundance ($\alpha = 2.2600$; $p = 0.038$), indicating that a one-unit increase in soil temperature was associated with an increase in mesofauna abundance of 2.26 units. Soil water content also exerted a positive effect on mesofauna ($\alpha = 0.5611$; $p = 0.050$). In contrast, soil pH showed a significant negative effect ($\alpha = -6.5580$; $p = 0.040$), indicating that increasing soil pH was associated with a reduction in mesofauna abundance. In Model IIB, soil temperature had a significant positive effect on soil microbial biomass (C-mic) ($\beta = 0.4603$; $p = 0.034$), indicating that each one-unit increase in soil temperature resulted in an increase of 0.46 units in microbial biomass. Soil pH exhibited a highly significant positive effect, with a coefficient of 2.7805 ($p < 0.001$), indicating that each one-unit increase in soil pH was associated with an increase of 2.78 units in soil microbial biomass. Model IIC showed that soil pH had a significant negative effect on earthworm populations (E-WORM) ($\beta = -0.1204$; $p = 0.028$), indicating that each one-unit increase in soil pH was associated with a decrease of 0.1204 units in earthworm abundance.

In Model III, soil microbial biomass (C-mic) had a positive effect on soil respiration (RESP), with a coefficient of 0.1692 at the 90% confidence level ($p = 0.075$), indicating that each one-unit increase in microbial biomass was associated with an increase in soil respiration of 0.1692 units. These results indicate that

increases in soil microbial biomass are associated with higher soil respiration, while other soil biota variables did not show significant effects.

Overall, this study confirms that soil respiration in pineapple plantations is primarily controlled by soil microbial components, and that soil management influences carbon emissions indirectly through changes in soil physicochemical properties and soil biota responses. These findings provide an important contribution to the development of process-based GHG accounting and support the implementation of more credible and scientifically grounded carbon trading mechanisms in the agricultural sector.

Keywords: biochar; carbon accounting; MRV; soil microbial biomass; soil management; soil properties; soil biota; soil water content; tillage.