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► **To cite this version:**

Jean Roger-Estrade, Pierre-Alain Jayet, Guy Richard. Coupling a Biophysical and a Microeconomic Model to Assess the Consequences of Compaction in Northern France. 18. Triennial Conference, International Soil Tillage Research Organisation (ISTRO). INT., Jun 2009, Izmir, Turkey. hal-01173051

HAL Id: hal-01173051

<https://hal.science/hal-01173051>

Submitted on 3 Jun 2020

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Coupling a Biophysical and a Microeconomic Model to Assess the Consequences of Compaction in Northern France

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Abstract: In Europe, soil compaction is a major problem with many consequences on production and environment. To assess the economic and environmental consequences of soil compaction at the regional scale, we combined a biophysical and an economic model. The coupled model simulated farmers' behaviour, taking into account soil, climate and crop management characteristics. The biophysical soil-crop model, named STICS, was coupled to an economic farm-group model, named AROPAj, at the regional scale. The coupling was based on response curves linking crop yield with the nitrogen inputs. The coupled model allowed us to assess N₂O emission, as a function of N inputs. The study shows that compaction induces sharp declines in gross margins for each crop and little change in the distribution of crops at the regional scale.

Key words: GHG emissions, soil compaction, biophysical modelling, economic modelling, GHG mitigation measures, economic policy.

INTRODUCTION

Soil compaction is a major process of physical soil degradation in Europe. In 1991, Oldeman et al., estimated that 33 million ha were concerned in Europe, which represented 4% of the agricultural soils. Since that time, preoccupation about soil compaction has grown, as a consequence of increasing size of agricultural machinery and average area cultivated by farmers (which implies more field operations carried out in wet conditions) and the development of reduced and no tillage. In France, all the agricultural soils are potentially concerned, which has consequences on the agricultural production (Alakukku, 2000; Stenitzer et Murer, 2003) and the environment. Indeed, compaction impedes root growth and functioning (Lampurlanès and Cantero-Martinez, 2003) and modifies the soil transfer properties, with consequences on erosion, carbon sequestration, nitrate leaching and denitrification (Quemada et al., 1997). The economic consequences of soil compaction should be considered in two parts. Firstly there is the possible private impact: the farmer is directly affected by his own decisions when he has

to deal with the yield decrease related to soil compaction. Secondly there are external (or public) consequences, like the impacts on greenhouse gas emissions which are directly related to the compaction, particularly because the microbial activity is affected by compaction. (Oorts et al., 2006). The whole economics of agriculture are now affected through environmental concerns and this should be taken into account by public regulation. In this paper, we present an approach where we coupled two models so that we could simulate the effect of soil compaction on yield, crop repartition and N₂O emission of these two types of economic regulation.

MATERIAL AND METHODS

Yield-response functions vary to a large extent with soil, climate and crop management practices. The required model to model these functions had to be able to reflect such diversity and to be adaptable to specific practices for nitrogen fertilisation at the European scale (integrating for instance a fertilisation schedule). The generic STICS model was selected for

its adaptability and its ability to simulate a wide range of crops and conditions of crop production in Europe. This model had been developed at INRA since 1996 (Brisson et al., 1998). It simulates crop growth as well as water and nitrogen soil balances, all dynamically driven by daily weather data. It uses information about soil and management practices as inputs. Agricultural variables (such as yield, input consumption) and environmental indicators (such as nitrogen and water losses) are computed by the model on a daily basis. The model was adapted to integrate soil compaction effects on crop growth directly through the root system dynamics (the roots growth rate and max depth were modified) and, more indirectly, through the changes in those soil properties that are affected by compaction (water infiltration, N and C mineralization, denitrification,...). This allowed modifying the yield response curves simulated by the model, as a function of the compaction degree of the soil.

AROPaj is a linear programming model which simulates the agricultural supply at the European Union scale (DeCara and Jayet, 2000; Godard et al., 2007). For a given economic situation, it provides an assessment of the type and amount of agricultural products delivered to the market and the surface allocated to each crop of the farm. This model was mostly used to study the successive reforms of the Common Agricultural Policy (CAP) of the European Union (Jayet and Labonne, 2005), but it has been used also to address global agri-environmental problems such as agricultural GHG emissions (DeCara et al., 2005).

For each crop of each regional farm-group, the model needs some technical data defining the crop management system used (tillage, sowing dates, sowing densities, cultivars, fertilization, irrigation, harvest date) and the soil characteristics (Brisson et al., 2002). Two set of climatic data were selected: the period corresponding to a winter wheat cycle in 2000-2001 (characterised by an autumn and a spring where rainfall markedly exceeded the mean values) and the winter wheat cycle 2004-2005 which was conversely characterised by a severe rainfall deficit during those two critical periods of the cycle. For a given set of inputs (i.e. a crop in a farm group on a compacted or

uncompacted soil), a variation of N fertilizer from 0 to 600 kg/ha (in steps of 20 kg/ha was applied for STICS simulations. The simulations were performed for the farm-groups of Ile de France, whose main industrial crops were simulated: wheat, barley, maize, sunflower, sugar beet and rape.

RESULTS

Effect of compaction on yields

Our simulations showed that, for the loamy soil considered, whatever the year, Yield was affected by compaction in the two studied areas and for all the crops taken into consideration. Table 1 shows that, in Ile de France, wheat yield was 2.9 t.ha⁻¹ (35 %) lower in the compacted soil compared to the uncompacted one when N supply was non limiting. Under the same conditions, mean reduction for corn yield due to compaction was 3.8 t.ha⁻¹ (43%). Our simulations showed also that, except for the wheat, consequences of soil compaction depended on the climatic conditions. Corn, sugar beet, rape and barley yields were more affected by compaction 2004-2005 (dry conditions in spring and fall) than in 2000-2001 (humid year). Conversely, sunflower was less affected in 2004-2005 than in 2000-2001.

N₂O emissions

Compaction increased dramatically, in the conditions of the STICS simulations (non limiting N supply to the crops), the N₂O emissions, and this, whatever the climatic year for all crops. The increase between NT and TT is very important with, for example, an increase of 20 to 27 kg.ha⁻¹ for the winter crops and comprised between 19 and 31 kg.ha⁻¹ for the summer crops. (Table 1). As for the yields, the results shown in Table 1 for N₂O emission exhibit a significant effect of the year they are more important in the humid year (2001) than in the dry year (2005).

Table 1. Yields and N₂O emissions for as simulated with the STICS model in Ile de France.
 NT: non-compacted soil and TT: compacted soil

| | | Yields* (t.ha ⁻¹) | | | | Annual N ₂ O emissions (kg N ₂ O.ha ⁻¹) | | | |
|-----------------|---------------|---|------|---|------|--|------|-----------|------|
| Years | Soils | 2000-2001 (humid conditions in spring and fall) | | 2004-2005 (dry conditions in spring and fall) | | 2000-2001 | | 2004-2005 | |
| | | NT | TT | NT | TT | NT | TT | NT | TT |
| Winter Crops | Wheat | 8.2 | 5.3 | 9.3 | 6.2 | 3.6 | 25.6 | 0.6 | 21.0 |
| | Rape | 3.2 | 2.4 | 4.0 | 2.3 | 5.6 | 32.6 | 0.5 | 23.8 |
| | Barley | 5.6 | 5.3 | 6.4 | 5.4 | 4.4 | 24.2 | 0.2 | 17.2 |
| Summer crops | Corn | 8.9 | 5.1 | 7.0 | 3.5 | 4.2 | 30.8 | 0.6 | 24.2 |
| | Sunflower | 3.6 | 2.3 | 2.8 | 2.0 | 4.6 | 35.6 | 0.3 | 13.8 |
| | Sugar Beet | 107.0 | 86.8 | 101.9 | 69.1 | 3.8 | 22.8 | 1.4 | 22.6 |

* N supply non limiting

Gross margins

Two Farm Types are found in the region Ile de France according to their technical and economic orientations (OTE): Farm producing only industrial crops (hereafter named industrial crop) and Farms. The gross margins for winter crops undergo the strongest reductions in margin (except for winter barley) which is consistent with the results usually observed in a wet year. The average reduction with a winter crop (barley not included) is 13.5% whereas it is only 10.6% with a summer crop. At the regional level (Table 2), the reduction of global gross margin is 5.8% for 2001 and 7.3% for 2005. In addition to the annual variation, the reduction of gross margin is related to the Farm-Type. Indeed, the mixed-farming farm-types don't obtain their margins only from the field crops and therefore undergo less the depressive effect of compaction on their economic results. Over the two years considered, the average reduction in gross margin is of 7% in field crops and 5.1% only in mixed-farming.

Table 2. Reduction of the global gross margin in Ile de France and for each of these Farm-Types for the years 2001 (wet) and 2005 (dry) when soil compaction is taken into account. The reduction is calculated as the ratio between the emission simulated with soil NT and the emission simulated with soil TT.

| Reduction of gross margin (%) | 2001 | 2005 |
|----------------------------------|------|------|
| <i>Region Ile de France</i> | 5.8 | 7.3 |
| <i>FT1 : Industrial crops</i> | 6.3 | 7.7 |
| <i>FT2 : Mixed Farming</i> | 4.2 | 6.0 |

Modelling the effect of mitigation measures on the regulation of the GHG emissions

In order to mitigate the total GHG emissions, and thereby the emissions of N₂O, we have simulated a scheme by taxing directly the GHG emissions. We studied the effects of an increasing tax on the GHG emissions ranging from 0 to 120 € per T-CO₂-eq emitted. Three mitigation targets of 4, 8 and 12% compared to the baseline emission level were defined. The values are presented in Table 3 for each year. As GHG emissions are smaller for 2005, higher taxes were necessary to reach a given mitigation target in 2004-2005 when the conditions were dry compared to the humid year (2000-2001). To reach a same target, 12% of N₂O mitigation, the tax is in 2004-2005 double than in 2000-2001.

This first-best tax on GHG emissions allows the public regulator to reach ambitious target of environmental damage abatement. However, such taxation is very costly to implement because each farmer's GHG emissions must be precisely known. Economically and practically speaking, this is not very realistic (it supposes to be able to measure these GHG or N₂O emissions in each field). That is why we have also to compare the first-best scheme with its alternative, a second-best scheme taxing the presumed factors of the environmental damage, i.e. nitrogen supply.

Table 3. Minimum threshold of tax on GHG emissions (€/T-CO₂eq) necessary to reach different objectives of mitigation

| Objective of N ₂ O emission reduction | 2000-2001 (humid conditions in spring and fall) | 2004-2005 (dry conditions in spring and fall) |
|--|---|---|
| 4% | 7.2 | 7.7 |
| 8% | 10.7 | 16.1 |
| 12% | 11.7 | 25.1 |

CONCLUSION

Environmental economics of agricultural inputs met wide interest, and nitrogen is a key item in this issue. However, in these studies, agronomical considerations, such as the effects of climate, soil characteristics or crop management are rarely mentioned. More specifically, the economic impact of soil compaction on farming systems and the environment has been rarely investigated. This work, coupling agronomical and economical models, deals

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simultaneously with the private impact – through the variation of yield and farm profit – and public impact – through the variation of nitrous oxide emissions – of soil compaction. We have quantified, at the regional scale, the effect of compaction on yield, N₂O emissions and gross margin. To assess the public impact of soil compaction, through the N₂O emission, the fertilizer tax has now to be studied.

ACKNOWLEDGEMENTS

This work was carried out under the project "Soil degradation due to compaction" with the financial support of (1) the « ANR- Agence Nationale de la Recherche - The French National Research Agency » under the « Programme Agriculture et Développement Durable », project « ANR-05-PADD-013 », (2) the Ministry in charge of Environment under the programme GESSOL2 « Impact des pratiques agricoles sur le sol et les eaux ».