Open Peer Review on Qeios

A Study for Estimation of Greenhouse Gas Emissions of Cotton in Central Greece

Vassilis Engonopoulos[1]

1 Agricultural University of Athens

Funding: Questionnaire survey, Bibliography, Publications, Articles.

Potential competing interests: No potential competing interests to declare.

Abstract

Cotton is an economically important crop in Greece, but few reports have systematically quantified the greenhouse gas emissions of Greece's cotton production and analyzed its causes. This study used the Cool Farm Tool (CFT) to identify the main components and driving factors of greenhouse gas (GHG) emissions of cotton production in Greece between 2020 and 2021 based on statistical data. The results showed that GHG emissions per unit region of cotton in Central Greece (Sterea Hellada and Thessaly) reached 2,126.10 kg CO_2-eq ha^{-1} or 460.8 kg CO_2eq t^{-1} yield, respectively. From 2020 to 2021, GHG emissions increased by 107.7 kg CO_2-eq ha^{-1} or 32.9 kg CO_2 eq t^{-1} yield due to increased number of irrigations and pesticide applications because of extremely high temperatures during the flower to open boll period. The multiple regression model showed that fertilizers were the main influence on carbon emissions. Improving the efficiency of cotton fertilization and ensuring the high-quality development of the cotton industry are effective strategies to reduce the carbon footprint of cotton cultivation in the future.

Vassilis Engonopoulos

Agricultural University of Athens, Department of Crop Science, Laboratory of Agronomy, 75 Iera Odos Street, 118 55, Athens, Greece

Keywords: Climate Change, Cotton, *Gossypium hirsutum,* Greece, Greenhouse Gas Emissions, Carbon Footprint.

Introduction

In recent years, consumers and the general public have become increasingly more cognizant of the environmental impact, through the emissions of greenhouse gases measured as carbon dioxide equivalent (CO_2e), from the production of goods and services they consume. Global corporate businesses, either through desire or market-driven necessity, are at the forefront of measuring and reducing their carbon footprint and in doing so, placing pressure on suppliers to reduce theirs. The impact of carbon emissions from agricultural enterprises and the role that the agricultural industry plays in the level of carbon emitted or sequestered continues to be debated, but current estimates suggest greenhouse gas emissions from agriculture account for 24 % of total greenhouse gas (GHG) emissions (IPCC 2007). A growing number of farmers are concerned and interested in establishing and monitoring their farm business' carbon emissions. There are reasons for doing this aside from the desire to assess and reduce their carbon footprint, which include identifying opportunities to improve nutrient utilization in a cropping enterprise, feed management and use for livestock, or to provide confirmation to domestic and overseas markets either to obtain access to a market or to receive a premium for the produce (FAO, 215; OECD 2011).

Human activities, including the burning of fossil fuels (such as coal and oil) and deforestation, are responsible for the increasing concentrations of greenhouse gases (GHG) in the atmosphere. GHG absorbs some of the energy radiated from the Earth's surface and traps it. The atmosphere essentially functions as a blanket that makes the Earth's surface warmer than it would otherwise be. The principal greenhouse gases (GHG) that are the main sources of global warming are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and three groups of fluorinated gases (sulfur hexafluoride SF6, HFC hydrofluorocarbons and PFC perfluorocarbons) (Myhre et al., 2013).

The global food production and distribution chain (Farm to Fork) is responsible for approximately 21– 37% of annual anthropogenic emissions (Poore et al., 2018; Mbow et al., 2019), but these emissions are dominated by methane (CH_4), which accounts for half of all anthropogenic methane emissions, and nitrogen oxide N_2O, which is three-quarters of anthropogenic N_2O (Mbow et al., 2019; Han et al., 2019). Carbon dioxide emissions are balanced by the exchange between CO_2 emitted into the atmosphere from agricultural practices and that which is absorbed by crop growth. The greenhouse gases that cause the greenhouse effect play a crucial role in climate change. Farming activities increase greenhouse gas emissions from the soil into the atmosphere through various agricultural practices such as irrigation and fertilization, which in turn affect the biogeochemical processes of carbon and nitrogen in the soil (Oertel et al., 2016).

In the agricultural sector, CO_2 comes from the microbial decomposition of organic matter that occurs in the soil or from the burning of crop residues. CH_4 is derived from the anaerobic decomposition of organic matter, and its main sources are the digestion process of ruminants, the storage of manure produced in intensive livestock farming and the cultivation of rice in bed (Mosier et al., 1998). N_2O is derived from the transformation of available nitrogen in soil and manure and is often emitted when soil nitrogen exceeds the plant's absorption capacity, especially in wet conditions (Oenema et al., 2005). In addition, agriculture is the main cause of the continuing change in land use, mainly through deforestation for crop production or pasture. Net CO_2emissions related to deforestation are estimated to be responsible for about 14% of the annual anthropogenic CO_2 (Le Quéré et al., 2018), which is directly related by 10% to agricultural production (Mbow et al., 2019).

The result of higher concentrations of greenhouse gases and rising temperatures will have direct and indirect effects on crop production, e.g., through the availability of water (rainfall and relative humidity) and the frequency of pests and diseases in crops (FAO 2015). Reducing greenhouse gas emissions during agricultural practices without reducing yields is an urgent and important task for all crops. Improving cultivation practices is a recommended strategy for reducing greenhouse gas emissions from cultivated regions. However, this strategy is highly dependent on farming techniques, as farming practices vary from crop to crop (Malhi et al., 2021)

Cotton is one of the major crops worldwide and delivers fibers to textile industries across the globe. Its cultivation requires high nitrogen (N) input in addition to irrigation, and the combination of both has the potential to trigger high emissions of nitrous oxide (N_2O) and nitric oxide (NO), thereby contributing to rising levels of greenhouse gases in the atmosphere. (Liu et al., 2010). These two factors are mentioned as the main sources of the emissions of greenhouse gases in cotton. The Greek cotton industry is labour, water and energy-intensive. Cotton production requires energy for ploughing, applying inputs (fertilizers, herbicides, insecticides, and plant growth regulators), planting, watering, crop cultivation, harvesting, slashing and transport. Crop intensification, mechanization and modernization have never been greenhouse gas (GHG) emission-free as they require the use of more fuel, farm machinery and inputs.

Given that 80% of the cotton produced in Greece is exported (European Commission 2018), its production must maintain product quality to remain globally competitive. It must also be efficient in its use of scarce resources and environmentally sustainable. With an increasingly carbon-conscious society and the imminent introduction of the Greek Government's Carbon Pollution Reduction Scheme (UNFCCC 2020), the cotton industry (as with other activities in the agricultural sector) needs research to provide accounts for all farm inputs related to GHG emissions. The aim of the present study is to estimate GHG emissions from three cotton farm plots associated with the major cotton-producing regions in Greece.

Specifically, the present study estimated GHG emissions due to: (1) soil-derived nitrous oxide (N_2O) from nitrogen (N) fertilizer usage; (2) agrochemical uses in cotton production; (3) electricity uses and combustion of fossil fuels used in cotton farm operations; (4) residues management; (5) transportation, and thus to identify which one makes the greatest contribution to the carbon footprint.

Materials and Methods

Geographical locations and climate of the study area

Farm plots were in three cotton regions in Central Greece (Sterea Hellas and Thessaly). The plots resembled each other in terms of soil structure, climatic conditions, and topography. Each sample plot is maintained by its respective grower.

In central-southern Greece, the climate is Mediterranean, with an average temperature of 24,50 C during cotton's cultivation period (mid-April – mid-October).

Table 1: Climatological data for Central Greece (Sterea Hellas and Thessaly).

Month	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*
Average high °C	16.3	20.9	25.25	28.38	28.6	24.1	18.63
Daily mean °C	14.80	20.33	25.53	27.37	26.40	22.27	16.83
Average low °C	7.68	12.0	16.17	19.13	19.51	16.46	12.23
Average precipitation mm	38.13	33.40	19.17	15.63	16.67	24.73	62.63

Table 2: Information for farm plots

Area	*No of Plots*	*Average Size of Plots ha 2020*	*Average Size of Plots ha 2021*	*Average Yield tn per ha 2020*	*Average Yield tn per ha 2021*
Kopaida Sterea	*4*	*8.97*	*9*	*4.85*	*4.55*
Elatia Sterea	*4*	*7.58*	*7.87*	*4.97*	*4.9*
Farsala Thessaly	*4*	*8.57*	*8.62*	*4.3*	*4.3*

Cultivation Practices

Land Preparation

It starts in early winter or in autumn. It begins with cutting of stalks and ploughing to cover plant residues and loosen the soil to a depth of about 20 cm. When soil moisture conditions permit during winter, chisels are used to loosen the soil surface and destroy weeds. In late winter or early spring, one or twice are used disc or tooth harrows to smooth the soil surface, improve the soil structure, and cover fertilizers, pesticides, and herbicides.

Planting

The planting period is roughly from the 10^{th} to the 30^{th} of April. For planting, four-row planters are used, equipped usually with fertilizers and pesticides applier. The distance between rows is 90 cm. Plant population varies from 200,000 – 250,000 plants/ha according to the variety and other factors, such as earliness, type of soil, etc.

Fertilizer Application

A common fertilization program implemented by many cotton growers includes the application of 300-450 kg N-P-K 20-10-10 per hectare at sowing (via the sowing machine) and another 250-350 kg N-P-K 20-10-10 per hectare during flowering (early summer).

Foliar fertilization in combination with insecticides is usually applied, especially in the early stages of plant growth.

The average yield was 4.46 tons per ha in response to the average fertilizer dose of 703 kg per ha.

Pesticide Application

Cutworms, wireworms, thrips, spider mites, whiteflies, jassids, bollworms and pink bollworms are the insect infestations of cotton in Greece.

Pesticide application in the field was recorded in terms of the number of applications and active ingredients used. An entire range of pesticides were used in the observation plots. Table 3 gives an indication of the types of pesticides used, number of sprays, and active ingredients applied.

Table 3. Information on the types of pesticides used in the farm plots

Corp Protection Input	***2020***	***2021***
Pentimethaline	Yes	Yes
Fluometuron	Yes	Yes
Chloropyrethos	Yes	Yes
Abamectin	Yes	Yes
Sulfoxaflor	Yes	Yes
Flonicamid	Yes	Yes
Chlorantraniliprole	Yes	Yes
Thiachloprid	Yes	Yes
Pyrethroids	Yes	Yes
No. of sprays per ha	7 to 9	9 to 11
Active ingredients in kg per ha	2.3 to 3	2.8-3.6

Harvest

The harvest normally occurs from mid-September to the end of October, depending on the variety and weather conditions and is machine-picked.

Soil type and irrigation

The soil in the plot's region is characterized as fine texture with good drainage and organic matter less than 1.72% and PH ranging between 7.3-8.5.

Table 4 below shows the soil type and the total quantity of water (in mm per ha) in each plot.

Table 4. Soil Types and net Irrigation water

REGION	SOIL TYPE	2020 IRRIGATION mm	2021 IRRIGATION mm
kopaida 1	loamy	345	450
kopaida 2	loamy	480	350
kopaida 3	loamy	343	314
kopaida 4	sandy loam	397	479
elatia 1	loamy	228	416
elatia 2	sandy loam	265	438
elatia 3	loamy	253	420
elatia 4	sandy	304	451
farsala 1	sandy loam	302	309
farsala 2	sandy loam	301	311
farsala 3	loamy	257	311
farsala 4	loamy	303	320

Data collection

A total of twelve farmers in the three regions were selected for data collection. The farmers of the sample plots were contacted individually to provide the information. Farm data was collected through a questionnaire divided into five groups.

In group 1 (Cultivation details), the cultivation area, quantity of fresh product (whole plant) and the quantity of final product were noted. Group 1 was also provided with data on waste management.

In group 2, soil characteristics were recorded, such as soil texture (clay, silty, sandy, etc.), soil organic matter, soil moisture, soil drainage as "good", and finally, the soil pH was noted.

For group 3, the choice of fertilization method and plant protection applications was made. More specifically, the type of fertilizer applied, the application dose and the evaluation of the measure (fertilizer units or product) were selected. The method of application (application in solution, dispersion, incorporation or hydro-lubrication - underground drip). Finally, the use of nitrification inhibitors was registered. Regarding the application of plant protection, a category was selected which describes the time and method of treatment (seed treatment, soil treatment or post-emergence) and the number of applications (doses) for each operation separately (weed control, leafing, etc.).

In group 4 (Fuels), the direct use of energy was noted, i.e., the energy source was selected, and the amount of energy (liters) used for this crop was entered. Consumption was noted for each task separately (plowing, cultivator, harrow, sowing, digging, fertilizing, growth regulator-plant protection-defoliation, irrigation, supervision visits and harvesting).

For group 5 (water use), it was noted how many times irrigation was done, by which method (shaft, irrigation pipe, flood or drop) and the water source (natural lake / pond, reservoir, river / stream / ditch or well drilling). Finally, the energy source (oil, e-electricity or gravity) used to irrigate the cotton was selected.

Estimation of GHG emissions during the cultivation phase

Cool farm tool (https://coolfarmtool.org/) was used in order to calculate greenhouse emissions. Cool Farm is a calculating tool for estimating greenhouse gas emissions, carbon footprint in a field based on yield and marketable yields, crop area, fertilizer applications (type and rate), number of applications of pesticides, and energy use (use of electricity and fuel). The use of the Cool Farm Tool creates incentives for climate-friendly agriculture and increased supply chain efficiency. The Cool Farm Tool has been mostly used in potatoes, maize, vegetables, coffee, and cotton. The tool was developed by the Cool Farm Alliance, which is constantly working on further improvements. The Cool Farm Alliance has 58 members, including food retailers, manufacturers, input suppliers, NGOs, universities, and consultants.

Results and Discussion

GHG emissions from inputs

The average GHG emissions for 2020 were 2,018.37 kg CO_2e ha^{-1} and 427.9 kg CO_2e kg^{-1} of seed cotton produced, and for 2021, were 2,126.10 kg CO_2e ha-^{1} and 460.79 kg CO_2e per kg of seed cotton produced (Table 5). In some related studies, total emission has been reported as 2,674 kg CO2e ha^{-1} for cotton production in Australia (Marseni T. et al., 2010), 1,195 kg CO2e ha^{-1} for cotton production in Iran (Pishgar-Komleh S. et al., 2012), and a range between 2,958 – 6,220 CO2e ha^{-1} for cotton production in China (Weibin H. et al., 2021).

The graphs below describe the emissions per year resulting from different sources (Figure 1a & 1b).

Figure 1a: CO2e (kg) emissions per hectare for residues management, fertilizer production, fertilizer application, crop protection, energy use and yield transportation to ginning mills.

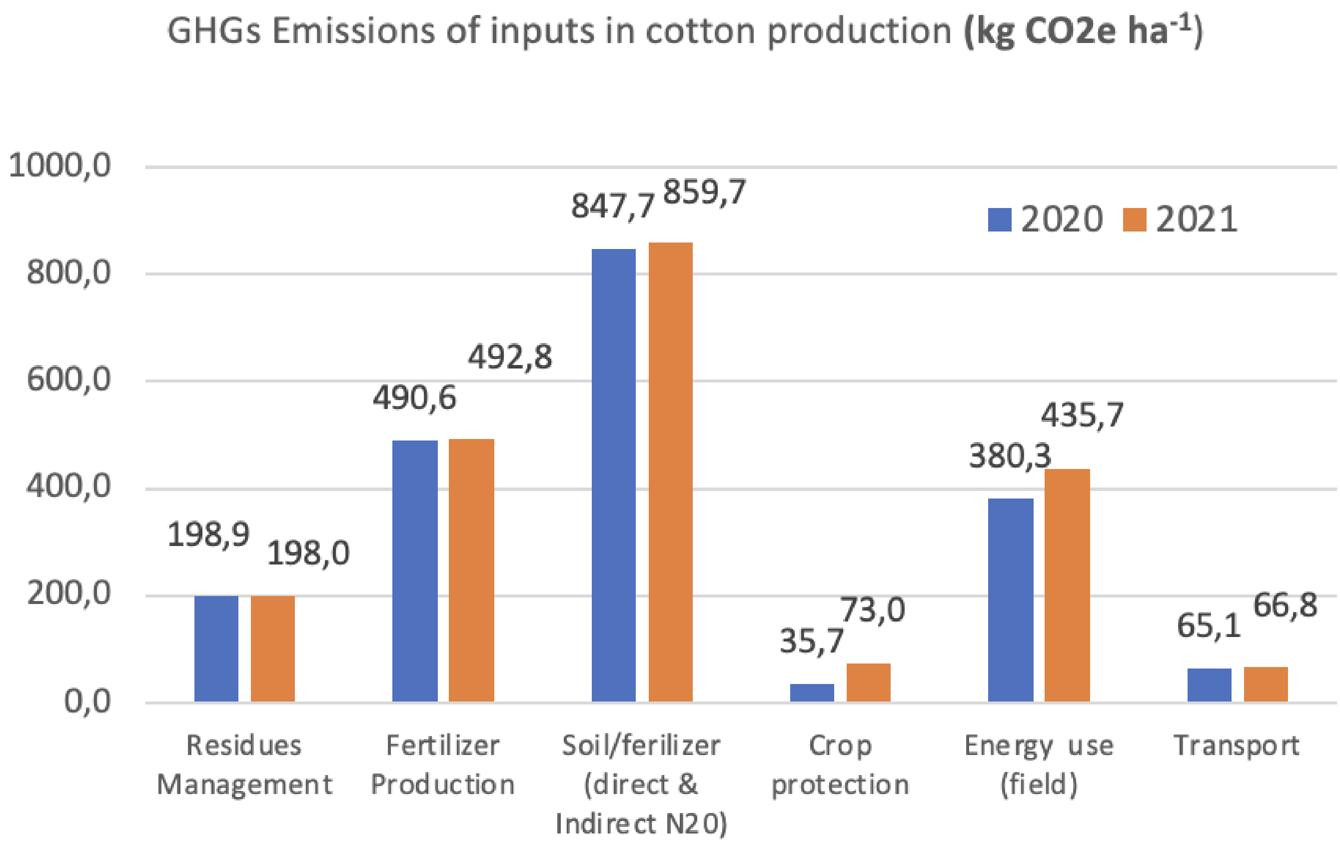

Figure 1a: CO2e (kg) emissions per hectare for residues management, fertilizer production, fertilizer application, crop protection, energy use and yield transportation to ginning mills.

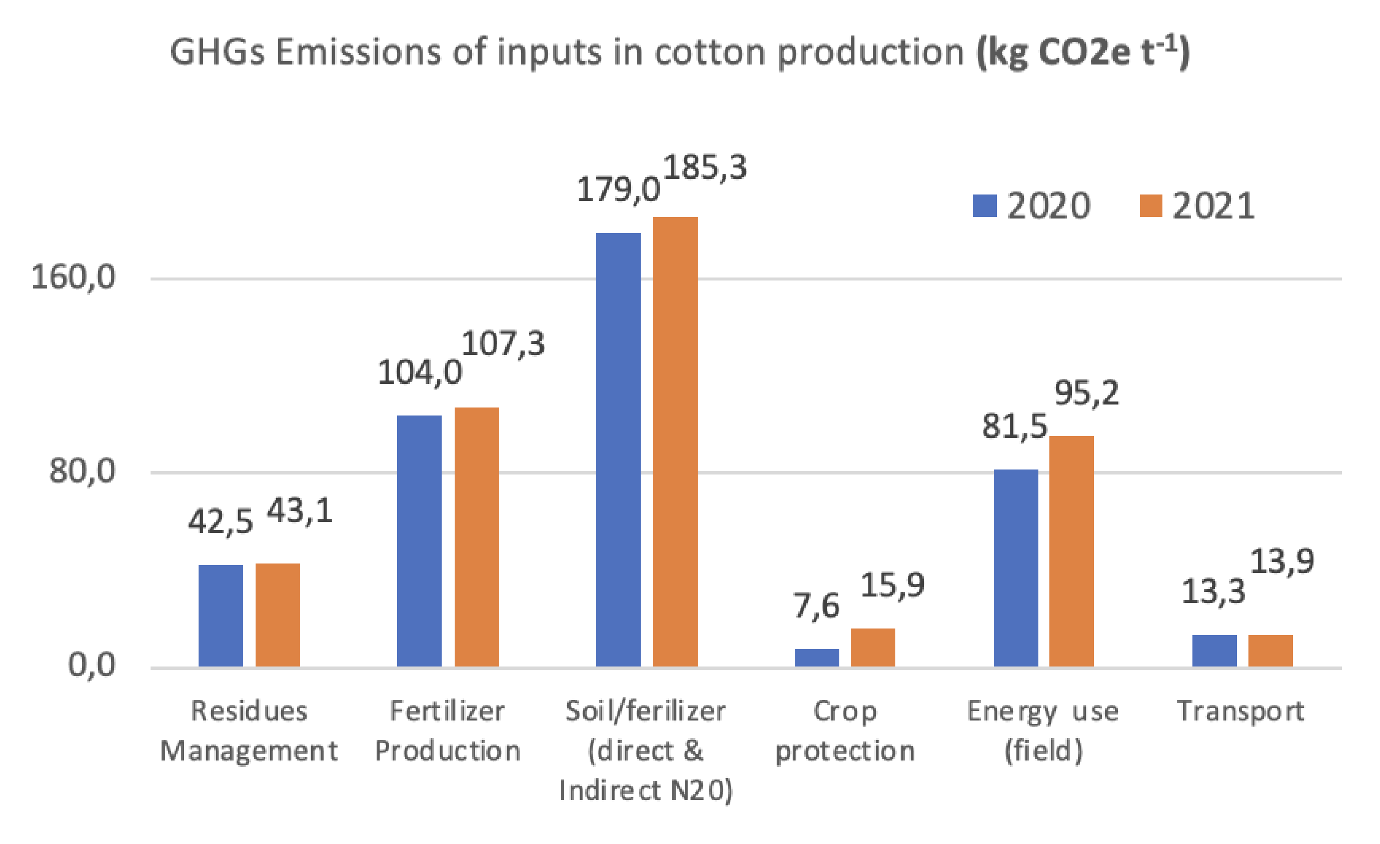

Figure 1b: CO2e (kg) emissions per tons of seed production for residues management, fertilizer production, fertilizer application, crop protection, energy use and yield transportation to ginning mills.

The above figures clearly indicate that the emissions resulting from fertilizer production, as well as fertilizer application (both direct and indirect N2O emissions), dominate the entire carbon footprint in cotton production. Emissions from energy used vary significantly in 2020 and 2021. Emissions resulting from transport are negligible in comparison to other sources.

As can be seen in Figure 2, fertilizer was the higher GHG emissive (with a proportion of 66% of the total emissions), followed by energy used in machinery operations and irrigation (19%), residue management (10%), and transportation (3%). The least GHG emissions belonged to crop protection inputs (2%). The results indicated the high GHG emissions for cotton production caused by the fertilizers. Other research studies denoted the high proportion of GHG emissions from fertilizers in cotton production (Marseni T. et al., 2010; Pishgar-Komleh S. et al., 2012).

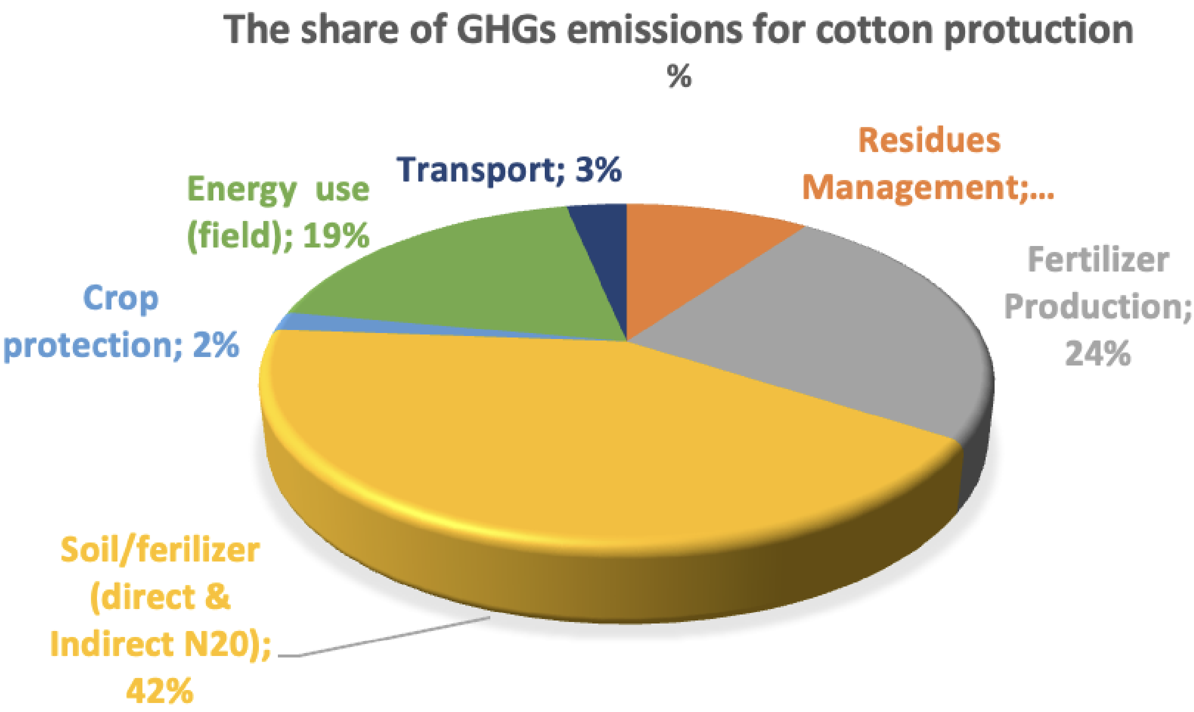

Figure 2. The share of GHG emissions for cotton production

A paired sample t-test was conducted to compare 2020 GHGs and 2021 GHGs in Table 5, revealing a significant difference in GHG emissions.

Table 5. GHG emissions in 2020 and 2021

2020	Kg $CO2e\ ha^{-1}$	t(11)=-3,812, p=0.003*
2021	Kg $CO2e\ t^{-1}$ yield	t(11)=-3,160, p=0.009*

** Significant at $p < 0.05$*

The subsequent increase in GHG emissions was mainly due to the increase in water demand and pesticide inputs because of extremely high temperatures in 2021, so the carbon intensity per unit of output rose.

GHG Emissions per region

The average GHG emissions per unit in Kopaida, Elatia and Farsala reached 1467.38 kg CO2e ha^{-1}, 2,851.4 CO2e ha^{-1}, 1,897.92 CO2e ha^{-1}, respectively, and the average GHG emissions per unit yield reached 312.84 CO2e t^{-1}, 577.94 CO2e t^{-1}, and 441.38 CO2e t^{-1} (Figure 3).

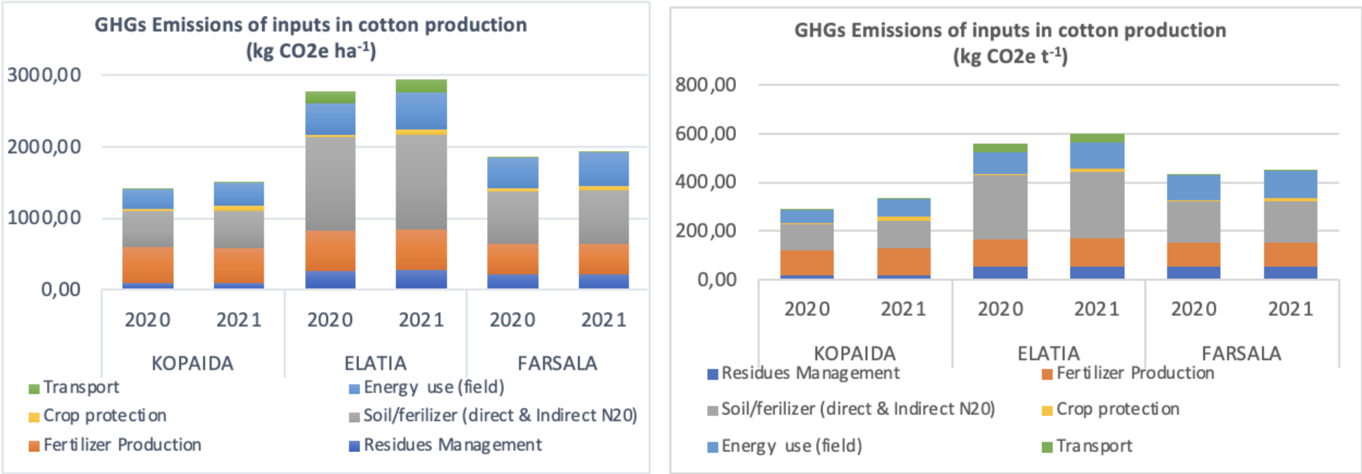

Figure 3. GHG emissions per region in 2020 and 2021

Compared with the average GHG emissions of Elatia, the emissions of Kopaida were 95% lower and 50% lower in Farsala. The results indicated an excessive use of fertilizers for cotton production in Elatia.

A one-way ANOVA was performed to determine if the GHG emissions of 2020 from the three different studying regions led to different test scores.

The ANOVA revealed that there was a statistically significant difference in regions (Table 6).

Table 6. Multiple comparisons of GHG emissions in the regions

Year	DF	MS	EV%	F
2020	2	1,886,781.636**	96%	122.60
2021	2	2,131,333.521**	96%	97.518

DF (Degrees of Freedom), MS (Mean Squares), EV% (percentage of the sum of squares)

*Major drivers of GHG emissions in the three cotton regions., ** significant at $p < 0.05$*

Analysis of GHG emissions from different sources in the cotton field

We analyzed the effect of GHG emission sources like the use of fertilizer, energy uses and pesticide application on overall emissions in both years' plots. The GHG emissions from two other sources (transport and residue management) are not considered because of their insignificant contribution to net emissions. We conducted a multiple regression analysis to understand the relationship between overall emissions and emissions from fertilizer, energy uses and pesticides.

Table 7. Effect of fertilizer applications, energy uses, and pesticide spraying on GHG emissions in plots.

Table 7. Effect of fertilizer applications, energy uses, and pesticide spraying on GHG emissions in plots.

Rl. No	Regressions Relations	adj.R^2
1	E = -221.436 + (1.268 * F) + (1.422 * En) + (0.148 * Pe)	0.99
2	E= -216.050 + (1.267 * F) + (1.432 * En)	0.99
3	E= 21.037 + (5.241 * En) - (1.599 * Pe)	0.61

E= Overall emissions in kg CO2 e ha-^{1}, F= emissions from fertilizers in kg CO2 e ha^{1}, En= emissions from energy use in kg CO2 e ha-^{1}, Pe= emissions from pesticides use in kg CO2 e ha^{1}.

A subsequent step-down analysis of each of the functions (emissions from fertilizers, energy use and pesticide emissions) is shown in Table 7. The step-down process eliminates each of the variables stepwise (as seen in the multiple regression relationships) to show the change in the overall emissions due to the absence of that variable. In the regression relation (Rl. No.3), where fertilizer emissions are stepped down, there is a considerable fall in R^2 value (from 0.99 to 0.61). From this, we can conclude that emissions from fertilizers are the major determinant in the overall emissions.

Fertilizer management is the most crucial management practice in terms of emissions. The following figure 4 indicates that emissions from fertilizer application (a sum of direct and indirect N2O emissions and emissions due to fertilizer production) contribute significantly to the overall emissions represented in kg CO2e/ha.

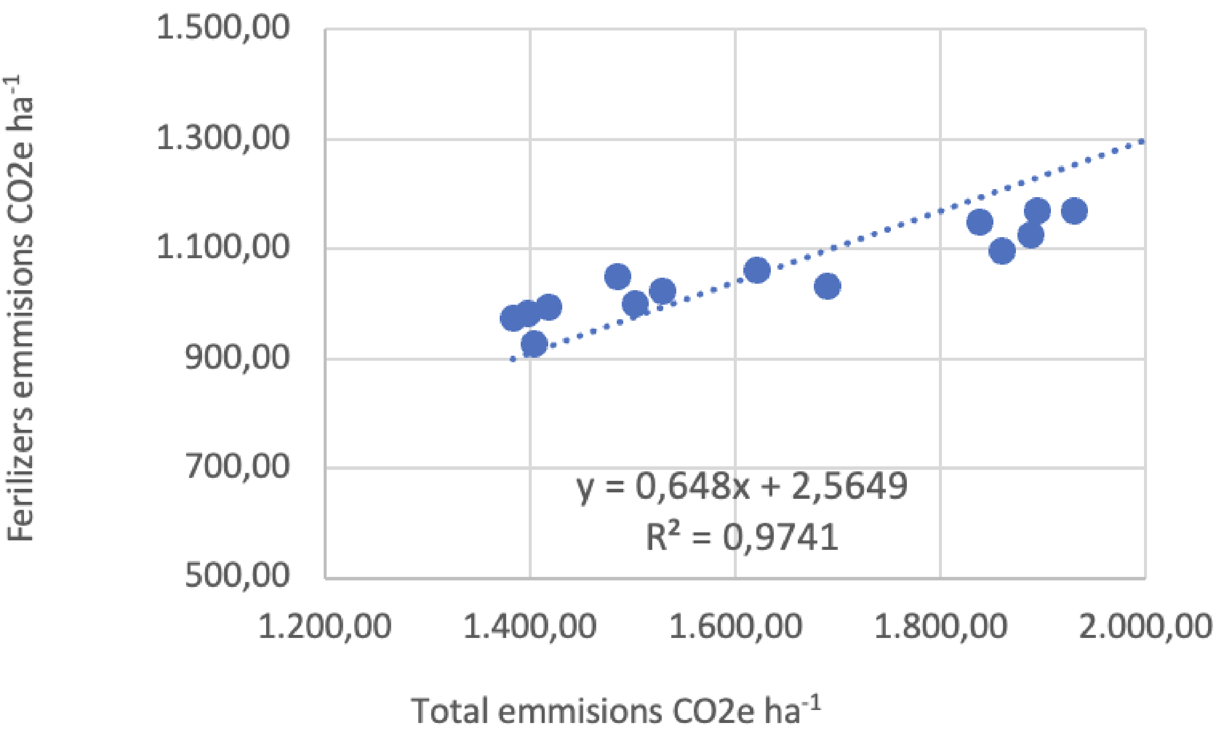

Figure 4. Regression between total emissions and emissions from fertilizer applications

The purpose of the study was to identify the sources of GHG emissions in selected cotton regions. The average GHG emissions per unit in Kopaida, Elatia and Farsala reached 1,467.38 kg CO2e ha-1, 2,851.4 CO2e ha-1, 1,897.92 CO2e ha-1, respectively, and the average GHG emissions per unit yield reached 312.84 CO2e t-1, 577.94 CO2e t-1, and 441.38 CO2e t-1 (Figure 1). Fertilizer was the higher GHG emissive with a proportion of 66% of total emissions.

Conclusions

Based on the results, to have better energy use efficiency value and decrease the GHG emission in cotton production, a better level of management in using fertilizer (mainly nitrogen), diesel fuel, machinery, and water for irrigation is needed (Pishgar-Komleh et al., 2012).

There are several ways to minimize the N2O emissions from soils (Maraseni T. et al., 2010) due to applied N-fertilizers, including:

(1) maintaining water-filled pore space at <0.4; (2) reducing soil compaction and thus increasing oxygen diffusion in soils; (3) reducing the readily available carbon supply, as this enhances microbial proliferation and N2O emissions; and (4) removing residual nitrate from the soil by growing cover crops (Dalal et al., 2003). In addition, the opportunity provided by injecting biochar into soils is becoming a very popular means for reducing N2O emissions and fostering long-term soil carbon sequestration (Lehmann et al., 2006; Yanai et al., 2007).

New techniques and technological advancements have helped growers to be more efficient with their nitrogen fertilizer use, making sure the plant has exactly what it needs when it needs it and not more. Precision agriculture management is the key to lowering nitrogen-based GHG emissions and uses a range of technologies to better measure and predict their crop's fertilizer needs, including sensors, drones, and sophisticated mapping and measurement tools (Balafoutis et al., 2017)

The increased adoption of conservation practices similarly reduces the quantity of applied nitrogen fertilizers (NASS Highlights, 3, May 2019).

The GHG emission estimates observed from the study in the farm plots are related to the inputs applied. They vary according to the changes in applied inputs regarding the geographical region, so they cannot be considered definitive figures for cotton cultivation in the region. However, the results give a clear indication of the potential for Agricultural Best Management Practices (BMPs) to reduce GHG emissions through balanced fertilization.

In conclusion, balanced fertilizer application at the recommended dose, an Integrated Pest Management System (IPM) and Precision Agriculture have the potential to reduce GHG emissions reduction.

References

- Balafoutis, A., Beck, B., Fountas, S., Vangeyte, J., Van der Wal, S., Soto, I., Barbero, M., Barnes, A., Eory, V. (2017). *Sustainability*, 9(8), 1339. https://doi.org/10.3390/su9081339.
- Cool Farm Tool. (n.d.). Method Papers. Retrieved from https://coolfarmtool.org/coolfarmtool/greenhouse-gases
- Dalal, R., Wang, W. J., Robertson, G. P., Parton, W. J., Myer, C. M., & Raison, R. J. (2003). Emission Sources of Nitrous Oxide from Australian Agricultural and Forest Lands and Mitigation Options. *National Carbon Accounting Technical Report No. 40*. Canberra: Australian Greenhouse Office.
- IPCC. (2007). *Climate Change 2007: The Physical Science Basis*. Cambridge University Press.
- FAO. (2015). Climate change and food security: risks and responses. Retrieved from http://efaidnbmnnnibpcajpcglclefindmkaj/https://www.fao.org/3/i5188e/I5188E.pdf
- Han, M., Zhang, B., Zhang, Y., & Guan, C. (2019). Agricultural CH4 and N2O emissions of major economies: consumption-vs. production-based perspectives. *Journal of Cleaner Production*, 210, 276–286. https://doi.org/10.1016/j.jclepro.2018.11.018
- Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304, 1623-1627.
- Lehmann, J. A., Gaunt, J., & Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems – a review. *Mitigation and Adaptation Strategies for Global Change*, 11, 395–419.
- Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., et al., (2018). Global carbon budget 2017. *Earth System Science Data*, 10, 405–448. https://doi.org/10.5194/essd-10-405-2018.
- Le Quéré, C., Jackson, R. B., Jones, M. W., Smith, A. J. P., Abernethy, S., Andrew, R. M., et al., (2020). Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. *Nature Climate Change*, 10, 647–653. https://doi.org/10.1038/s41558-020-0797-x.
- Liu, C., Zheng, X., Zhou, Z., et al., (2010). Nitrous oxide and nitric oxide emissions from an irrigated cotton field in Northern China. *Plant and Soil*, 332(1-2), 123–134.
- Malhi, G. S., Kaur, M., & Kaushik, P. (2021). Impact of Climate Change on Agriculture and Its Mitigation Strategies: A Review in *Sustainability*. https://doi.org/10.3390/su13031318.
- Maraseni, T. N., Cockfield, G., & Maroulis, J. (2010). An assessment of greenhouse gas emissions: implications for the Australian cotton industry. *Journal of Agricultural Science*, 148, 501–510. https://doi.org/10.1017/S002185960999058X.
- Masson, V., Delmotte, H.-O., Pörtner, D. C., Roberts, P., Zhai, R., Slade, S., Connors, S., van Diemen, S. (2019). *Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.*
- Mbow, C., Rosenzweig, C., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., et al., (in press) *Food security*, in *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*, eds P. R. Shukla, J. Skea, E. Calvo Buendia, V.
- Mosier, A.R., Duxbury, J.M., Freney, J.R., Heinemeyer, O., Minami, K., Johnson, D.E. (1998). *Mitigating agricultural emissions of methane*. *Climatic Change, 40*, 39-80.

- Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, D., et al., (2013) *Anthropogenic and natural radiative forcing*, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, and J. Boschung, et al., (Cambridge; New York, NY: Cambridge University Press), 659–740.
- OECD (2011). *A Green Growth strategy for food and agriculture: Preliminary report.* Retrieved from www.oecd.org/greengrowth/sustainable-agriculture/48224529.pdf.
- Oenema, O., Wrage, N., Velthof, G.L., van Groenigen, J.W., Dolfing, J., Kuikman, P.J. (2005). *Trends in global nitrous oxide emissions from animal production systems*. *Nutrient Cycling in Agroecosystems, 72*, 51-65.
- Oertel Cornelius, Matschullat Jörg, Zurba Kamal, Zimmermann Frank, Erasmi, Stefan (2016). *Greenhouse gas emissions from soils—A review*. *Geochemistry, Volume 76, Issue 3, 2016*, Pages 327-352, ISSN 0009-2819, https://doi.org/10.1016/j.chemer.2016.04.002.
- Pishgar-Komleh, Seyyedhassan & Sefeedpari, Paria & Ghahderijani, Mohammad. (2012). *Exploring energy consumption and CO2 emission of cotton production in Iran*. *Journal of Renewable and Sustainable Energy, 4*. https://doi.org/10.1063/1.4727906.
- Poore, J. and Nemecek, T. (2018). *Reducing food's environmental impacts through producers and consumers*. *Science, Vol 360, Issue 6392*, pp. 987-992, https://doi.org/10.1126/science.aaq0216.
- UNFCCC (2015). *Paris Agreement*.
- Vermeulen, S. J., Campbell, B. M., and Ingram, J. S. I. (2012). Climate change and food systems *Annual Review of Environment and Resources, 37*, 195–222. https://doi.org/10.1146/annurev-environ-020411-130608
- Weibin Huang, Fengqi Wu, Wanrui Han, Qinqin Li, Yingchun Han, Guoping Wang, Lu Feng, Xiaofei Li, Beifang Yang, Yaping Lei, Zhengyi Fan, Shiwu Xiong, Minghua Xin, Yabing Li, Zhanbiao Wang. Carbon footprint of cotton production in China: Composition, spatiotemporal changes and driving factors. *Science of The Total Environment, Volume 821*. https://doi.org/10.1016/j.scitotenv.2022.153407
- World Wildlife Fund, India (WWF-India). Cutting cotton carbon emissions: findings from Warangal, India, May 2013. https://www.eldis.org/document/A65408
- Yanai, Y., Toyota, K., & Okazaki, M. (2007). Effects of charcoal addition on N2O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments. *Soil Science and Plant Nutrition, 53*, 181–188.