INDEPENDENT SCIENTIFIC EXPERT ASSESSMENT OF THE *SCARABAEUS* PROJECT (No. J05-LVPA-K-01-0095)

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EXECUTIVE SUMMARY

Sapropel is a freshwater lake organic-mineral sediment complex. Sapropel is extracted from lakes, dewatered and its colloidal structure is then modified. The processed sapropel is applied to contaminated, degraded or infertile soils as a fertilizer and conditioner. It is a sustainable, natural and slowly renewable resource that is present in large quantities in Eastern Europe. Lithuania has the largest sapropel reserves within the European Union (estimated to be 1.5-2.0 Billion tonnes). Laboratory and field investigations have demonstrated that sapropel treatments can significantly improve agrophysical, agrochemical, microbiological and biochemical properties of degraded and infertile soils and increase agricultural crop yields.

The Lithuanian SME GJ Magma of Vilnius is implementing Project No. J50-LVPA-K-04-0095 (funded by EU Structural Funds). The Project is developing innovative technology designed for the potential use of sapropel as an ameliorant/soil conditioner. These experiments are being conducted in Serapiniškės gravel/sand quarry in the Trakai district of south-east Lithuania (54.612116^{o}N, 25.012753^{o}E). The research team includes scientists from Lithuania, Latvia and Belarus. The Serapiniškės test field was established on 15/05/19.

The Serapiniškės quarry soils are 91% sand, 8% gravel and 1% fines (silt and clay). The soil organic matter (SOM) content was low (0.17%) and soil pH was high (9.15). Thus, the soils replicate characteristics generally associated with arid soils (Aridisols).

Fully-replicated experiments were undertaken in 2019 and 2020 and the experimental schedule for 2021 is on-going. Soil and crop analyses were performed by Certified Laboratories and data are subjected to appropriate statistical analyses. A novel aspect of the research is the tractor-led system (‘*Scarabaeus*’), which is used to insert sapropel to the rooting zone (rhizosphere) of the planned rotation of crops (i.e. 10-25 cm depth). This addresses the obvious concern that transporting large quantities of sapropel to arid regions would be prohibitively expensive.

The ‘*Scarabaeus*’ system proved effective in delivering sapropel to the rhizosphere. The usual application rate of Sapropel is 60 t/ha. However, this application rate is not financially viable, considering transport costs to arid countries. The experiments made a targeted application equivalent to 10.6 t/ha in the rhizosphere (i.e. 17.7% of the usual field application rate). Treatments included 10.6 t/ha of sapropel by traditional surface application; 60.0 t/ha of sapropel by traditional surface application, ‘*Scarabeus*’ laboratory prototype (one-row) at 10.6 t/ha and ‘*Scarabeus*’ industrial prototype (two rows) at 10.6 t/ha.

In 2019, the studied crops were: radish, lettuce, maize, faba beans, common beans, potatoes, cabbages, carrots, red beet, celery and leeks. In 2020, the studied crops were: maize, potatoes, onions, common beans, cabbage, radish, leeks, lettuce, faba beans and red beet.

Analysed soil physico-chemical properties included SOM and concentrations of total soil nitrogen (N), total soil phosphorus (P), total soil potassium (K) and soil magnesium (Mg). Complementary measurements were made of the chlorophyll content of leaves, soil temperature, soil electrical conductivity, soil moisture and soil conductivity. All analytical

temperature, soil electrical conductivity, soil moisture and soil conductivity. All analytical techniques adopted internationally-recognised protocols and thus the data are of repeatable quality.

Careful review of the 2019 and 2020 data and observations led to the following conclusions:

1 The *Scarabaeus* system uses a relatively small amount of soil conditioner (*circa* 20% of the usual field application rate), hence transport costs from source to market are financially viable. Dewatering and modification of the colloidal structure of sapropel is essential to achieve and maintain the sustainable properties of the soil ameliorant.
2 Ameliorants produced from sapropel application improved soil nutrient status, provided soil organic matter, improved soil moisture retention and decreased soil pH to levels suitable for crop production. Thus, the artificial soil produced using the innovative technology of the 'Scarabaeus' system was a suitable substrate for crop production.
3 Ameliorants produced from sapropel applied via the *Scarabaeus* system at the 10.6 t/ha rate was equally effective as the field application of 60 t/ha in maintaining the soil fertility necessary for crop production. Furthermore, there is evidence of less nutrient leaching from soil treated with the *Scarabaeus* system, particularly less leaching of nitrogen. The vegetation parameters of the plants obtained in the test field and comparative yield calculations show that the parameters of *Scarabaeus* technology declared by UAB GJ Magma enabled decrease in the established ameliorant insertion rate by up to five-fold.
4 The insertion of soil ameliorants to targeted depths proved effective. In 2019 the crop yields of maize, faba beans, common beans, potatoes, cabbages, celery and leeks were significantly higher ($P < 0.05$) on *Scarabaeus* treated soils. In 2020, these effects were significant ($P < 0.05$) for lettuce, maize, onions, common beans, cabbage, leeks, faba beans and red beet.
5 The insertion of ameliorants at 10-15 cm depth protects the materials from subsequent deep cultivation, sowing and harvesting processes. Furthermore, the ameliorants are also protected from exposure to the sun and erosion (by both wind and water). Hence, the inserted ameliorant remains *in situ* and is not damaged by subsequent tillage operations (i.e. shallow cultivation, sowing and harvesting processes) for three-four years.
6 In some instances, the crop root system did not penetrate to the conditioner-enriched lower topsoil. Therefore, significant crop effects were not evident for carrots in 2019 or radish or potatoes in 2020. Progress requires careful matching of the crop characteristics with the depth of ameliorant.
7 The *Scarabaeus* system proved effective on very sandy soils which are generally unsuitable for crop production. This provides evidence that the system may well prove effective on comparable soils (Arenosols). Suitable agro-environmental conditions may include sandy soils in arid zones (Aridisols) with associated irrigation/fertigation systems.
8 Generally, the '*Scarabeus*' industrial prototype had relatively greater crop responses than the '*Scarabeus*' laboratory prototype.
9 There were statistically significant ($P < 0.001$) effects of soil treatment on soil biota (soil respiration rates, enzymatic activity, and the diversity and biomass of bacterial and fungal populations).
10 The evidence does accord with the premise that the *Scarabaeus* system merits support and further investigations and investment. The system has potential to improve agro-

environmental conditions on sandy infertile soils in multiple climatic conditions. Therefore, the *Scarabaeus* system could prove a practical commodity for sale both in the East European agricultural market and in the broader international agro-technology market.

The preliminary evidence that the *Scarabaeus* system is effective in infertile sandy soils, leads to the following recommendations and suggestions:

1 The Serapiniškės field experiment should continue for at least a further year (2021).
2 It is recommended a fully-replicated soil sampling and analysis programme is undertaken each year for at least two-three years. In addition to the current schedule of analysis, it is recommended that soil samples are also subjected to full textural and mineralogical analysis.
3 A three-year (plus) chronosequence of experiments at Serapiniškės would be highly suitable for publication in a high-impact international journal.
4 Given that a working hypothesis is that a single insertion of sapropel into sandy soils is effective for four to five years, a more prolonged five-year experiment is recommended.
5 It is probable that repeat insertion of sapropel-based ameliorants (e.g. every four or five years) would promote pedogenic processes, which would progressively encourage the development of fertile topsoils (A horizons).
6 It is suggested that the *Scarabaeus* system be field tested in arid pedo-climatic field conditions (e.g. in Israel and Spain).
7 There is considerable potential to produce composite sapropel-based soil conditioners. These could include sapropel, oligotropic (acid) peats, zeolites, glauconite, phosphogypsum and additional minerals. This offers opportunities to develop specific high-value composite soil conditioners customized for targeted applications (e.g. for use on Aridisols). Such engineered soil conditioners have considerable potential to be registered as patents.
8 The *Scarabaeus* system has potential to:
   (a) Restore the agronomic properties of degraded soil.
   (b) To create a fertile artificial soil on land affected by desertification process in arid zones for a limited period of 4-5 years per insertion.
   (c) Improve crop productivity on organic farms.
   (d) Facilitate the intelligent use of sapropel resources.
   (e) Promote considerable commercial opportunities in terms of investment, SME development and employment.

Therefore, it is recommended that proposals are made to the European Commission (e.g. HORIZON EUROPE) for further product research and development.

INTRODUCTION

SAPROPEL (freshwater lake organic-mineral sediment complex) extraction and application can be used in multifunctional agro-environmental and pharmaceutical technologies. Field and laboratory experiments indicate sapropel can decontaminate polluted soils, with the additional benefits of improving the properties of polluted, degraded and infertile soils. Use of sapropel can create artificial fertile soil for a limited period of four to five years on land which is unsuitable for vegetation growth. Sapropel products can also be used for pharmaceutical and therapeutic applications. Sapropel management can contribute to carbon sequestration and thus contribute to decreased rates of global warming.

Sapropel deposits are natural capital and extraction effects lake water quality and resources. Extraction and application of sapropel effects soil chemistry, biology and crop production. Extraction of sapropel cleans source-lakes, thus maintaining their ecological integrity and preventing the lakes from deteriorating into unproductive marshland.

Sapropel is an organic-mineral sediment complex, which can be extracted from lakes, dewatered and processed (typically by modifying its colloidal properties) to create the requisite properties necessary for use as a sustainable soil conditioner. The processed sapropel can then be applied to contaminated and degraded soils as a fertilizer and/or soil conditioner. Sapropel can also be applied to soils affected by desertification processes to create the properties necessary for crop production. Sapropel is a sustainable, natural and slowly-renewable resource that is present in large quantities in Eastern Europe, including the Baltic States. Laboratory and field investigations have demonstrated that sapropel treatments can lead to distinct improvements in the physico-chemical properties of degraded and infertile soils and increase agricultural crop yields (Baksiene *et al.*, 2006). Sapropel may have the potential to remedy contaminated soils. Theoretically, the organic colloids of sapropel could conduct this ‘soil-cleaning’ function. Therefore, before sapropel is more widely endorsed, there is an urgent need to provide a thorough and rigorous evaluation of the benefits and potential challenges of its application as an innovative, sustainable and affordable soil technology and its impacts on the environment and the food chain (Booth *et al.*, 2007). This includes evaluations on the effects of sapropel on ‘sources’ (i.e. the aquatic ecology of sapropel lakes) and ‘sinks’ (i.e. contaminated and degraded environments, such as desertified field environments).

Intelligent use of sapropel resources could be integrated into carbon management strategies and thus contribute to decreasing the rate of global climate change. By maintaining lakes as active sinks of atmospheric carbon by sapropel deposition, much carbon can be sequestered in lake sediments. Typically, sapropel depth increases by 2-3 mm/yr. However, a ‘conveyor-belt’ approach is needed (Van Oost *et al.*, 2007), as the system requires lake water bodies to function as carbon sequestering systems and this function will cease if lakes are converted into unproductive marshland. Thus, intelligent use of sapropel resources directly accords with European Commission policies and supports the objectives of the Water Framework Directive, Common Agricultural Policy, the Soil Thematic Strategy and the Bioeconomy 20-20-20 targets.

The application of ameliorant produced from sapropel is known to benefit the agrophysical, agrochemical, microbiological and biochemical properties of degraded soils. The organic colloids of sapropel should act as chelating agents, chemically ‘locking’ anionic soil contaminants and thus effectively removing them from biogeochemical cycles. This should be a relatively simple technology to remedy soil contamination. Sapropel provides a rich source of organic matter. Moreover, chemically, sapropel contains most macro- and micro-nutrients necessary for full and successful plant and crop growth. These include the macro-nutrients nitrogen (N), phosphorus (P), potassium (K) and calcium (Ca) and the micro-nutrients manganese (Mn), zinc (Zn), boron (B), copper (Cu) and iron (Fe). Furthermore, sapropels accommodate relatively low quantities of cellulose decomposing bacteria, supporting slow mineralization and enabling prolonged fertilizer-life, compared with other organic fertilizers (Orlov and Sadovnikova, 1996). For instance, increasing soil organic matter content influences water retention capacity, the capacity of extractable bases to supply macro- and micro-nutrients, soil aggregate stability, soil aeration and concomitantly decreases physical degradation (compaction, surface sealing and crusting) and soil erodibility.

Sapropel constituents include bioactive substances, including vitamins, enzymes and antibiotics (Kershaw, 1997). There have been few evaluations of possible pharmaceutical and/or therapeutic applications of sapropel (Orbidans *et al.*, 2009; Vysokogorskii *et al.*, 2009; Krivonos and Plaksin, 2010). Evidence suggests that certain sapropels possess various biological and pharmacological properties, notably, antimicrobial and antioxidant properties, and may have the potential for pharmaceutical applications. However, there are no reports on any systematic evaluation of the bioactivities of sapropels in terms of their potential uses in pharmaceutical formulations and purification of active components.

SAPROPEL AS A GLOBAL RESOURCE

Historically, sapropel has a long history of use. Sapropel was used as a soil conditioner by ancient Colombian and Egyptian civilisations (European Commission, 2019). Sapropel is currently used in Chinese agriculture (Plate 1). At present, the main sapropel extraction and application is in East European countries. Lithuania has the largest sapropel reserves within the European Union (estimated to be 1.5-2.0 Billion tonnes. In addition, estimated reserves in Latvia are 1.5 Billion tonnes and 1.2 Billion tonnes in Estonia. Estimated reserves in Belarus are over 4 Billion tonnes, and over 100 Billion tonnes in the Russian Federation.

The scientific consultants of the *Scarabaeus* Project implemented by UAB GJ Magma are Professor Nicolaj Bambalov and Dr Guennadi Sokolov from the National Academy of Sciences of Belarus (Minsk). They have investigated the fundamental physico-chemical and biological properties of sapropels (Bambalov and Sokolov, 1998, 2000; Bambalov, 2013; Agafonova *et al*., 2015). They have also made progress in investigating the potential of these sapropels to improve the agricultural potential of arid soils, specifically in Egypt (field investigations 1994-96), the United Arab Emirates (UAE) (1989-99) and the Kingdom of Bahrain (2002-04). They emphasized the importance of the properties of sapropel being properly evaluated prior to field applications. Thus, the sapropel should be unpolluted (i.e. without contamination by heavy metals, such as lead (Pb)). In addition, the sapropel should also be non-sodic and non-calcareous, as Aridisols tend to have high sodicity and high pH values. To maximize the potential of sapropels, the Belorussian team have ‘bioengineered’ composite materials, termed ‘SATOR’ (Sokolov and Bambalov, 1998; Solokov, 2013). SATOR consists of bespoke and customized mixes of sapropel, oligotrophic (i.e. acid) peats, zeolites (volcanic minerals) and the minerals glauconite and phosphogypsum. In this Project, GJ Magma is using an ameliorant with a similar composition. Belarusian scientists shared their experience with SME GJ Magma specialists on using sapropel ameliorant in arid zones. They also provided support regarding analytical protocols and methodology.

Plate 1. A sapropel island in Lake Er-Hai, Yunnan Province, south-west China. The crop of garlic is exported as a high value cash crop to Japan (photo M.A. Fullen, January 2008).

SAPROPEL EXPERIMENTS IN LITHUANIA USING THE ‘*SCARABAEUS*’ SYSTEM

The Lithuanian SME GJ Magma of Vilnius is implementing Project No. J50-LVPA-K-04-0095. This Project is funded by EU Structural Funds and is developing innovative technology designed for the potential use of sapropel as an ameliorant/soil conditioner. These experiments are being conducted in Serapiniškės gravel/sand quarry in the Trakai district of south-east Lithuania (54.612116^{o}N, 25.012753^{o}E). The Project is being implemented in collaboration with the Latvia University of Agriculture (Jelgava) and Vytautas Magnus University Agricultural Academy. The Project is also being advised by a group of scientists from the National Academy of Sciences in Belarus. This group has been conducting field research in arid zones using ameliorants produced from sapropel. The Serapiniškės test field was established on 15/05/19. The soils were sampled within the established 300 m^2 (6x50 m) test plot (Plate 2).

The aim is to simulate arid environmental conditions, to both test the efficacy of sapropel in very sandy soils and to create artificial fertile soil for a limited period of 4-5 years. The quarry soils are 91% sand and 8% gravel and 1% fines (silt and clay). Moreover, the soil organic matter (SOM) content was 0.17%, a value typical of arid soils (Fullen *et al*., 1995). In addition, soil pH was high (9.15). Such a high pH is inimical to crops, due to caustic action and sodium (Na) toxicity damaging plant roots and due to the chemical 'locking' of potential nutrients. Thus, the soils replicate characteristics associated with arid soils (Aridisols, in the US Soil Taxonomy; Arenosols, Calcisols and Gypsisols in the World Reference Bureau Classification, WRB) (European Commission, 2019). Thus, the simulation is realistic in a pedo-environmental context. However, understandably, it is not possible to replicate the climatic conditions of hot arid environments in the field. These conditions have been partly addressed using two greenhouses. The greenhouses also protect crops from weather damage (from wind and precipitation).

Field experiments were undertaken in 2019 and 2020 and the experimental schedule for 2021 is on-going. Soil and crop analyses were performed by Certified Laboratories in Latvia and Lithuania. The experiments are well-designed and data are subjected to appropriate statistical analyses (i.e. One-Way Analysis of Variance (ANOVA); Analysis of Least Significant Differences (LSD at $P < 0.05$ and $P < 0.01$) and Pearson correlation coefficients).

Plate 2. Field experiments in Serapiniškės gravel/sand quarry in the Trakai district of south-east Lithuania.

A novel aspect of the research is the design of a tractor-led agricultural machine (‘*Scarabaeus*’) to insert sapropel into the rooting zone (rhizosphere) (i.e. 10-25 cm depth), with insertions at distances 50-70 cm. Spacing is designed to optimize crop production for the planned crop rotation of crops. This technology reduces the rate of ameliorant insertion by a factor of five (Figure 1, Plate 3). The decreased insertion rate addresses the obvious concern that transporting large quantities of sapropel to arid regions would be prohibitively expensive.

The *Scarabaeus* system proved effective in delivering sapropel to the rhizosphere. Supportive evidence includes multiple photographs from shallow soil pits. The research team have carefully monitored the field performance of the *Scarabaeus* system and it has proved successful in fulfilling its specified role. The team also are modifying the prototype to optimize the amount and depth of soil conditioner application. Having a system which can be modified to optimize performance in multiple arid environments (i.e. for different soil and crop conditions) would enhance the applicability of the system. The emplacement of ameliorants at 10-15 cm depth protects the material from subsequent shallow cultivation, sowing and harvesting processes. Furthermore, the ameliorants are also protected from exposure to the sun and erosion (by both wind and water).

The usual application rate of Sapropel is 60 t/ha. Such a dose was determined experimentally by scientists from the National Academy of Sciences of Belarus, led by Academician N. Bambalov. For several years Academician Bambalov conducted research using ameliorants produced from sapropel in arid countries (i.e. Egypt, the United Arab Emirates (UAE) and the Kingdom of Bahrain). Using an application rate of 60 t/ha of ameliorant from sapropel, the team obtained crop yields comparable to yields on the fertile Nile Delta (Kheir *et al.,* 2019). This application rate is not financially viable, considering the costs of ameliorant extraction, processing and subsequent transport to arid countries. The Serapiniškės experiments made a targeted application equivalent to 10.6 t/ha in the rhizosphere (i.e. 17.7% of the established rate of sapropel ameliorant used in arid zones by Belorussian scientists). Treatments included 10.6 t/ha of sapropel by traditional surface application; 60.0 t/ha of sapropel by traditional surface application, ‘*Scarabeus*’ laboratory prototype (one-row) at 10.6 t/ha and ‘*Scarabeus*’ industrial prototype (two rows) at 10.6 t/ha.

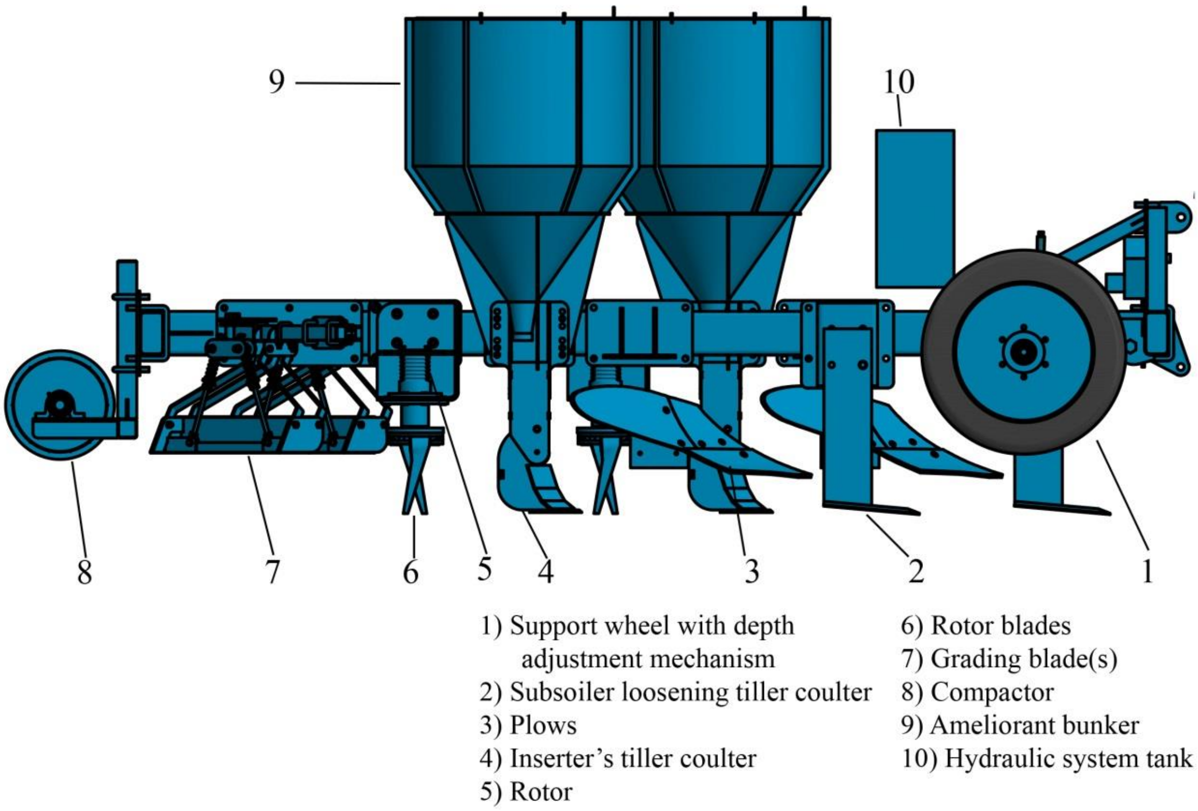

Figure 1. Design of the *SCARABAEUS* system.

In 2019, the studied crops were: (1) radish, (2) lettuce, (3) maize, (4) faba beans, (5) common beans, (6) potatoes, (7) cabbages, (8) carrots, (9) red beet, (10) celery and (11) leeks. In 2020, the studied crops were: (1) maize, (2) potatoes, (3) onions, (4) common beans, (5) cabbage, (6) radish, (7) leeks, (8) lettuce, (9) faba beans and (10) red beet.

Soil physico-chemical properties were analysed. These included analysis of soil organic matter (SOM) and concentrations of total soil nitrogen (N), total soil phosphorus (P), total soil potassium (K) and soil magnesium (Mg). Complementary measurements were made of the chlorophyll content of leaves, soil temperature, soil electrical conductivity, soil moisture and soil conductivity. All analytical techniques adopted internationally-recognised protocols and thus the data are of repeatable quality. In 2020, daily meteorological readings (precipitation (mm) and air temperature (^{o}C)) were taken.

Plate 3. Tractor and *SCARABAEUS* system at the Serapiniškės field site.

Sapropel applications provided the essential nutrients for crop growth and decreased soil pH to values suitable for crop growth. Usually, soil pH values of *circa* 5.5-6.5 are ideal for most temperate crops. Sapropel typically has a pH of 5.2-6.0. Therefore, non-calcareous sapropel, peat and other mildly acidic media can be used to alter soil pH to desired levels. The added organic matter also improved soil moisture retention within treated soils.

Field experiments evaluated the response of selected crops. Crop responses were evaluated by multiple measurements, including crop biomass (both fresh and dry-weight), crop density and crop height. Statistically significant ($P < 0.05$) increases in crop growth were evident for most crops in terms of control versus the four sapropel treatments.

In 2019, increased crop yields were statistically significant ($P < 0.05$) for the effects of the *Scarabaeus* system on radish, lettuce, maize, faba beans, common beans, potatoes, cabbages, red beet, celery and leeks. The response of carrots was not significant.

In 2020, significant ($P < 0.05$) effects of sapropel treatments (including use of the *Scarabaeus* system) were evident in terms of the crop responses of lettuce, maize, onions, common beans, cabbage, leeks, faba beans and red beet. Usually, the *Scarabaeus* system had either no significant difference from the high-rate of sapropel application or was significantly higher. This evidence suggests the *Scarabaeus* system with a low-dose of sapropel (10.6 t/ha) is at least as effective as a traditional sapropel treatment (60 t/ha).

In 2019, the non-significant responses of both radish and carrots can be attributed to the shallow nature of the crop roots not penetrating to the depth of the sapropel layer. In 2020, the non-significant responses of both radish and potatoes may also be attributed to insufficient root penetration. Evidence supports the assertion that the *Scarabaeus* system should be amenable to modification of field operation protocols to optimize nutrient uptake from the rhizosphere.

Direct soil treatment effects on soil biota were evident from the application of soil ameliorants. In soil samples taken from 0-10 and 10-20 cm in 2019, sapropel significantly increased soil respiration, biomass of microorganisms and enzymatic activity. There was also evidence of developing symbiotic activity in terms of nitrogen-fixation associated with interactions between sapropel and the legume crops faba beans and common beans peas. Thus, it appears that sapropel is initiating a process of pedogenesis, including developing mechanisms to enhance nitrogen-fixation in the developing soil.

Soil samples were taken from 0-20 cm in 2020 (06/11/20). Effects were statistically significant ($P < 0.001$) for the effects of sapropel on soil microbial populations (including colonies of both ammonifying and nitrifying bacteria and 10 taxa of soil fungi). Overall, treatment increased the cultivable bacterial population by a factor of 150 and the soil fungi population by a factor of 10. The significant effects ($P < 0.001$) were consistent in the four sampled crops (beans, leeks, potatoes and maize) and was strongest in the topsoil associated with the crop of leeks.

Generally, the '*Scarabaeus*' industrial prototype (SI) had relatively greater crop responses than the '*Scarabeus*' laboratory prototype (SL). In 2020, in the case of maize cobs (fresh weight) and onions (crop density and bulb weight, both fresh and dry), the crop productivity of SI was significantly ($P < 0.05$) higher than SL.

SUMMARY OF FINDINGS

GJ Magma provided the reviewer (Michael A. Fullen) with a full and comprehensive portfolio of information (including technical reports, videos, photographs, conference presentations, patent certificates and PowerPoint presentations). All data have been collated and verified by internationally-recognised agronomic research institutions (i.e. Vytautas Magnus University, Kaunas and Vilnius, Lithuania; and the Latvia University of Agriculture, Jelgava). Scientists from the National Academy of Sciences of Belarus have also collaborated in the research programme and shared their experience of the effects of sapropel on Aridisols in Egypt, the United Arab Emirates and the Kingdom of Bahrain.

Careful review of the 2019 and 2020 data and observations led to the following conclusions:

1. Since the *Scarabaeus* system uses a relatively small amount of soil conditioner (*circa* 20% of the usual field application), then transport costs from the source to market (i.e. arid countries) is financially viable.
2. Since *circa* 95% of the fresh weight of sapropel is water, dewatering is essential to achieve viable transport costs and to retain the essential properties of the ameliorant.

The 'B3 Snowgun' (patented by the Project Manager P. Steponavičius) is an effective initial stage in the de-watering process, decreasing overall water content from *circa* 95% to *circa* 55%.

3. Ameliorants produced from sapropel and peat applications improved soil nutrient status, provided soil organic matter, improved soil moisture retention and decreased soil pH to levels suitable for crop production. Thus, the modified soil was a viable substrate for crop production.
4. Ameliorants produced from sapropel applied via the *Scarabaeus* system (10.6 t/ha) was equally effective as the field application of traditionally applied 60 t/ha in maintaining the soil fertility necessary for crop production. Furthermore, there is evidence of less nutrient leaching from soil treated with the *Scarabaeus* system, particularly less leaching of nitrogen.
5. The insertion of soil ameliorants to targeted depths proved effective in significantly increasing the crop yields of maize, faba beans, common beans, potatoes, cabbages, celery and leeks (in 2019), and lettuce, maize, onions, common beans, cabbage, leeks, faba beans and red beet (in 2020).
6. The emplacement of ameliorants at 10-15 cm depth protects the material from subsequent shallow cultivation, sowing and harvesting processes for three-four years. Furthermore, the ameliorants are also protected from exposure to the sun and erosion (by both wind and water). Hence, the integrity of the inserted ameliorant remains intact.
7. In some instances the crop root system did not penetrate to the conditioner-enriched lower topsoil. Therefore, significant crop effects were not evident for carrots in 2019 or radish or potatoes in 2020. Progress requires careful matching of the crop characteristics with the depth of ameliorant.
8. The *Scarabaeus* system proved effective on very sandy soils which are generally unsuitable for crop production. This provides evidence that the system may well prove effective on comparable soils (i.e. Arenosols in the World Reference Bureau System; European Commission, 2019). Suitable agro-environmental conditions may include sandy soils in arid zones with associated irrigation and/or fertigation systems.
9. The soil conditioners used in the field experiments included sapropel mixes with peat. The evidence suggests the system could prove effective in multiple soil treatments, where targeted application to shallow soil depth is required.
10. Generally, the '*Scarabeus*' industrial prototype had relatively greater crop responses than the '*Scarabeus*' laboratory prototype.
11. Direct soil treatment effects on soil biota were evident from the application of soil ameliorants produced from sapropel. In soil samples taken in 2019, sapropel significantly ($P < 0.001$) increased soil respiration and enzymatic activity. There was also evidence of developing symbiotic activity promoting nitrogen-fixation associated with interactions between sapropel and the legume crops faba beans and common beans. Further soil samples were taken from 0-20 cm on 06/11/20. Effects were statistically significant ($P < 0.001$) for the effects of sapropel-based ameliorant on soil microbial populations (including colonies of both ammonifying and nitrifying bacteria and 10 taxa of soil fungi). Overall, treatment increased the cultivable bacterial population by a factor of 150 and the soil fungal population by a factor of 10. The significant effects ($P < 0.001$) were consistent in the four sampled crops (beans, leeks, potatoes and maize) and was strongest in the topsoil associated with the crop of leeks.
12. The evidence does support the premise that the *Scarabaeus* system merits support and further investigations and investment. The system has potential to improve agro-

environmental conditions on sandy infertile soils in multiple climatic conditions. Therefore, the *Scarabaeus* system could prove a practical commodity for sale both in the East European agricultural market and in the wider international agro-technology market.

RECOMMENDATIONS FOR FURTHER RESEARCH

The preliminary evidence suggests that the *Scarabaeus* system is effective in infertile sandy soils. Based on this evidence, the following recommendations are proposed:

1. The Serapiniškės field experiment is now entering the third year. Continuation of the experiment is desirable, as the evidence is being progressively improved in both space and time.
2. It is recommended a fully-replicated soil sampling and analysis (minimum 3-samples per treatment, recommended 5-samples per treatment to strengthen statistical analyses) is undertaken for the next two-three years. In addition, it is recommended soil samples are subjected to full textural analysis, in particular analysis of the silt/clay fraction. X-Ray Diffraction (XRD) analysis of clay mineralogy is also recommended.
3. A three-year (plus) chronosequence of experiments at Serapiniškės would be highly suitable for publication in a high-impact international journal. Typically, such journals require at least three-years of fully-replicated field experiments to be accepted for publication.
4. Given that a working hypothesis is that a single insertion of sapropel into sandy soils is effective for four to five years, a more prolonged five-year experiment is recommended.
5. It is probable that repeat insertion of sapropel-based ameliorants (e.g. every four or five years) would promote pedogenic processes. These processes would progressively encourage the development of fertile topsoils (A horizons) (Fullen *et al*., 1995).
6. It is suggested that the *Scarabaeus* system be field tested on Aridisols in arid pedo-climatic conditions. Preliminary discussions have progressed concerning possible field experiments in Israel and Spain. Given the advanced nature of arid-land agricultural technology in these two countries, such field experiments are highly desirable.
7. There is considerable potential to produce composite sapropel-based soil conditioners. These could include sapropel, oligotropic (acid) peats, zeolites, glauconite, phosphogypsum and additional minerals. This offers opportunities to develop specific high-value composite soil conditioners customized for targeted applications (e.g. for use on Aridisols). Such engineered soil conditioners have considerable potential to be registered as patents.
8. Given the issues related to the transport costs of bulky products to arid countries, it is recommended that where a bioengineered sapropel product is to be transported, as much as possible of the additives are sourced from local supplies in the specific arid country. This could apply to manures, specific minerals and additives introduced in fertigation schedules.
9. The *Scarabaeus* system has potential to:
   (a) Restore the agronomic properties of degraded soil.
   (b) To create artificially fertile soil in land affected by desertification process in arid zones for a limited period of four to five years per insertion.
   (c) Improve crop productivity on organic farms.
   (d) Facilitate the intelligent use of the sapropel resources.

(e) Promote considerable commercial opportunities in terms of investment, SME development and employment.

Therefore, it is recommended that proposals are made to the European Commission (e.g. HORIZON EUROPE) for further product research and development.

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