UTOPUS: A NOVEL TRACTION MECHANISM TO MINIMIZE SOIL COMPACTION AND REDUCE ENERGY CONSUMPTION

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Abstract

Tractor tires on agricultural soil suffer from inherent limitations like energy loss due to slip and tire flexing and a need for considerable ballast to gain traction. These limitations contribute to soil compaction, make the agricultural tractor energy-inefficient and make it unviable to power a tractor with solar panels or by storing renewable energy in batteries.

To address these disadvantages as a whole, we introduce a novel traction mechanism that allows weeding and cultivation using only autarkic solar energy, based on the novel principle of retractable tines or crampons for traction. The mechanism inserts relatively small crampons every few meters into the soil, and then uses a push-pull mechanism to pull tillage implements through the soil, without any additional ballast. The light weight of the resulting machine and the small contact area of crampons with the soil reduce soil compaction, while the static nature of the crampons minimizes energy loss and increases energy efficiency.

We report a range of successful proof-of-concept trials which show the practical feasibility of the basic concept for weeding and soil cultivation with solar energy, wind energy, and electric power supply under different conditions. We also provide calculations on the economic advantages compared to ballasted tires.

Keywords: Crampons, Push-Pull Locomotion, Inching Locomotion, Energy Efficiency, Tractive Efficiency, Soil Compaction

1. Introduction

Ever increasing soil compaction and high energy consumption greatly limit the usefulness of current agricultural vehicles, to the point where the consensus is that the less a vehicle enters the field, the better. To achieve traction on soil, a wheeled vehicle needs to be ballasted such that the downward force of the ballast is about 2.5 times the required draft force on all agricultural soils (Zoz and Grisso, 2003). That is, for every Newton N of draft force which acts horizontally on the surface between tire and soil, the ballasted vehicle needs to apply 2.5 N of weight to the same surface. The combined force vector measures 2.7 N for every N of draft and presses diagonally downwards into the soil at the rather steep angle of 68˚ from horizontal, see Figure 1. This combined force compresses the region of soil under the tire into a compact body which can resist the horizontal shear force and allows the vehicle to move forward. The compacted soil under the tire does not remain entirely static. It is shorn horizontally, increasing the damage to soil structure, see Figure 2.

This compaction has several undesirable effects. The soil under the tire is compressed into a continuous rut which is a pathway for water erosion. The compacted soil has lost fertility due to reduced root penetration (Bengough et al., 2011), reduced soil aeration (Whalley et al., 1995), reduced water infiltration and reduced water storage (Ankeny et al.,1990), and due to erosion from excess runoff (Fullen, 1985), see Figure 3. Compacted soil requires significantly stronger and deeper tillage, which greatly increases machinery cost and energy consumption, and leads to a vicious cycle of ever bigger machinery to till soil which is compacted to ever increasing degree and depth (Håkansson and Reeder, 1994). Considering a global shortage of fertile agricultural land, loss of soil fertility due to compaction is neither sustainable nor acceptable. And if traffic invariably damages soil then it is difficult to develop robotic solutions for precision agriculture where robotic vehicles enter the field to fertilize, control pests, or harvest as needed.

Even though these problems have been studied and published for well over 60 years, the available solutions offer only limited respite, and never abandon the fundamental principle of locomotion through vertical soil compression[1]. Tracks spread the weight over a longer section of the rut, which somewhat decreases the volume of compressed soil, but shears the soil badly when steered (Hamza et al., 2005). Controlled traffic aims to limit compaction to permanent ruts in the field, sacrificing a significant portion of soil in the process. No-till can avoid some tractor traffic, but not all, while the associated dependency on herbicides leads to other problems like herbicide resistance and environmental degradation.

Large tractors require large homogeneous fields, which are more vulnerable to pests. So, the economies of scale of current machinery increase dependency on pesticides and favor pesticide resistant genetically modified (GM) crops over local well-adapted varieties, which in turn reduces the available gene pool and resilience to future hazards. Minimum and no-till offer an increasingly cost-effective alternative to tillage while helping to control erosion, but again at the cost of increased dependence on pesticides and with no respite from machine induced compaction of the soil.

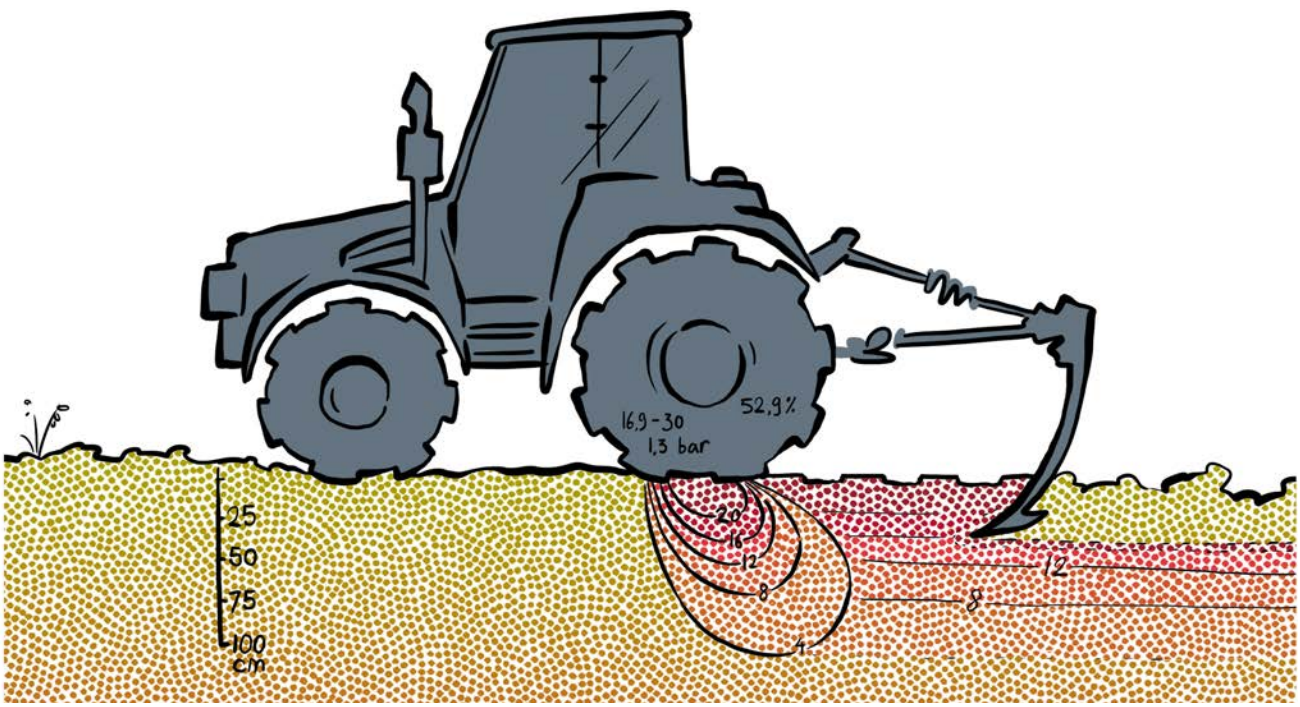

Fig. 1. *The main axis of the pressure bulb under a tractor tire extends diagonally into the ground and compacts the soil below the depth of tillage (Söhne and Bolling, 1981).*

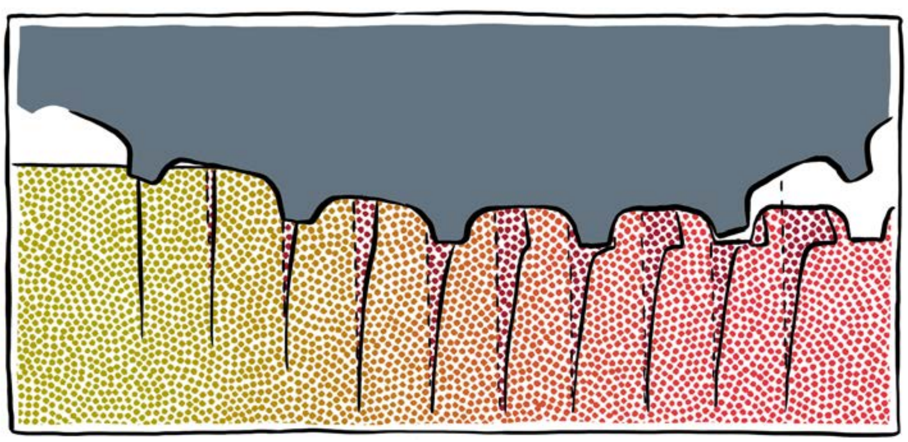

Fig 2. *The horizontal sheer force of the tire damages the soil just as much as the ballast (Söhne, 1952).*

[1] With the notable exception of cables, a solution which reappears periodically since pre-industrial times. This solution consists of an engine powered by wind, steam, or other means, which moves along the headland at one end of the field, together with a counterpart on the opposite headland, and which uses cables to pull an agricultural tool back and forth between the engine and the counterpart.

Advances in autonomous control and navigation allow us to replace heavy machinery by a fleet of lighter, driverless robots, which creates opportunities for more diverse agriculture, with field sizes not being arranged simply to suit heavy machines. This in turn creates opportunities to deploy natural pest resistance, increasing the diversity of genotypes by creating a value for local varieties over GM crop. However, even small wheel-based vehicles compact and shear the topsoil and have a relatively high fuel consumption.

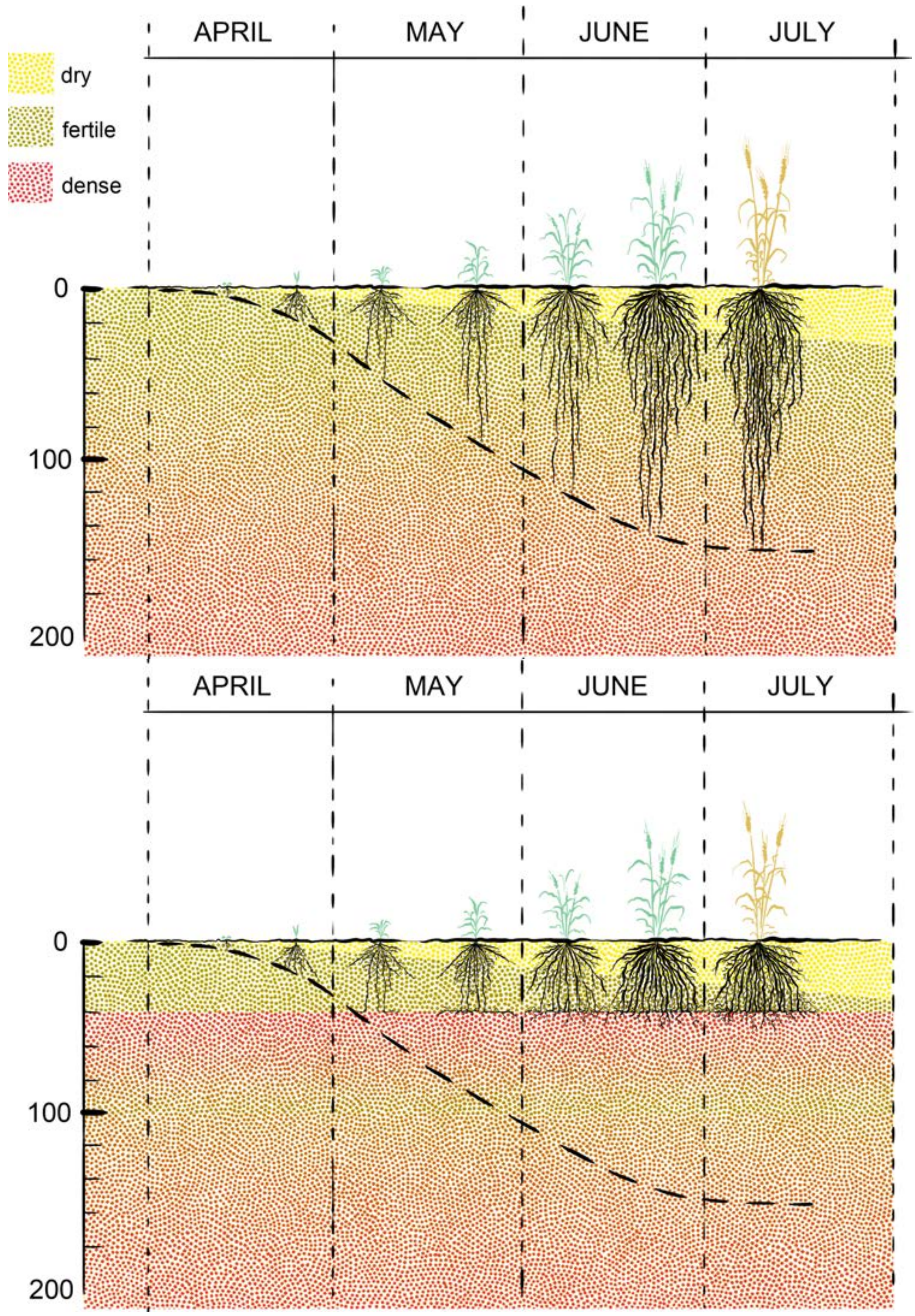

Fig 3. *The effect of soil compaction on root growth.* ***Top:*** *In healthy soil wheat roots utilize the soil column to a depth of 120 cm.* ***Bottom:*** *In compacted soil root growth is mostly limited to the plowed top soil, which dries out quickly in arid climates.*

2. The UTOPUS traction mechanism

The present article proposes to abandon the principle of locomotion through ballasted tires or tracks altogether, and to replace it by a push-pull mechanism based on retractable tines or crampons, which we call the UTOPUS traction mechanism (Bover, 2011, Nannen et al., 2016). It is well known that a narrow stake like a tent peg can resist considerable horizontal force when anchored in soft soil. If more resistance is needed, the peg can be driven deeper into the soil, or a second peg can be added. Why not use the same principle to generate traction on loose soil?

We will use the term “crampon” to denote a retractable peg or tine which is used to generate traction or pull. A crampon provides a point of resistance from which a tillage implement can be pulled through the soil without power loss to tire slippage and without the motion resistance of tires and without creating ruts from tire treads that can be the pathways to erosion. As crampons eliminate the need for ballasted tires, they promise to minimizes soil degradation through compaction. The use of crampons for traction requires engineering solutions to establish

- the proper shape and configuration of the crampon so that it enters and leaves the soil easily and without significant damage to the subsoil and so that it provides maximum pull resistance when in the soil,
- an efficient, robust, and reliable mechanism to periodically drive a crampon into the soil to the desired depth and to pull it out again,
- a push-pull mechanism to move a vehicle from a set of static crampons.

A crampon can generate traction if and only if its rearward motion resistance in the soil (its rearward draft) is significantly greater than the forward draft of the tillage implements which it pulls. The tractive efficiency of a crampon depends on the energy it costs to anchor it, and how firmly it will hold in place. A crampon is anchored by driving it into the ground with force. The energy required to drive it into the ground increases with its width and with its depth in the soil. The rearward draft it generates increases with its width, its depth in the soil, and its angle in the soil. These draft forces have been studied extensively both theoretically and empirically by a number of scientific studies of the draft of narrow tines (Hettiaratchi et al. 1966; Hettiaratchi and Reece, 1967 and 1974; Godwin and Spoor, 1977; McKyes and Ali, 1977; Grisso and Perumpral, 1985). The motivation for these studies was to minimize the draft of a narrow tine which is used for tillage. The present invention tries to maximize draft. The physical laws that govern the draft are the same. Godwin and Wheeler (1996) study soil penetration and maximum sustainable pull of a broad land anchor and find that models based on the equations of Hettiaratchi et al. and Godwin and Spoor agree with the measurements.

The above studies show that a narrow tine which enters the soil at an angle of 90˚ from horizontal produces the highest draft force or traction, while at 60˚ from horizontal the traction will be only half of this draft force for a given depth. For this reason it is important that the crampon will rotate into a position perpendicular from horizontal after being driven into the soil. The articles also show, but with less agreement, that when the width of a crampon is increased by a certain factor x, the draft increases by a factor y smaller than x. Assuming, however, that the energy required to drive a crampon into the soil grows linearly with width, the authors consider that it is more efficient to have a narrow crampon that anchors deeply than a wide crampon that does not anchor deeply, not the least because a narrow crampon can be expected to result in less damage to the soil structure during the insertion process than a wider tool and because the deeper soil layers provide more soil strength. Factors which affect soil strength include shear strength and soil density. The value of these properties at a given depth depends on the weight of the soil column above it, which causes the soil particles to be packed tighter and to interlock. See Figure 4 for an illustration of a possible design of a narrow crampon to pull a tillage implement.

In order to drive the crampons into the soil in a robust and reliable way, without the need for additional actuators, the authors suggest a simple design as illustrated in Figure 5. The crampon, which consists of multiple tines, is fixed to the rear of a moving frame by a horizontal hinge and is shaped such that when resting on the ground, its tip is pointing backwards at the ground. When the frame is pushed or pulled backwards, the tip of the crampon scratches the soil and starts to penetrate the soil, partly under its own weight and partly as a reaction to the resistance of the soil. The more the crampon penetrates the soil, the more soil resistance it encounters, which forces it deeper and deeper into the soil, until its soil resistance is higher than the draft force of the tillage implement it has to move. In this way the crampon will penetrate only as deep as is necessary in order to move the tillage implement.

Since the resistance of agricultural soil displays high spatial variability (Watts et al. 2006), once the crampon is anchored and the plow it pulls or pushes starts to move forward, the soil resistance encountered by the plow often increases significantly within a meter or less of plowing distance, such that the resistance encountered by the plow becomes greater than the resistance originally provided by the anchor. When this happens, the anchoring mechanism as described here simply pushes the crampon even deeper into the soil, until the resistance encountered by the crampon is again greater than that of the tillage implement. Due to this self-regulating mechanism, the crampon will be pushed only as deep into the soil as is needed to plow a given patch of soil, which is energy efficient and minimizes disturbance of the subsoil. The authors find that a curved crampon design like in Figure 4 and 5 helps the crampons to penetrate the soil efficiently and reliably. Note that with a curved design the part of the crampon which penetrates the subsoil reaches an angle of close to of 90˚ from horizontal, which maximizes soil resistance.

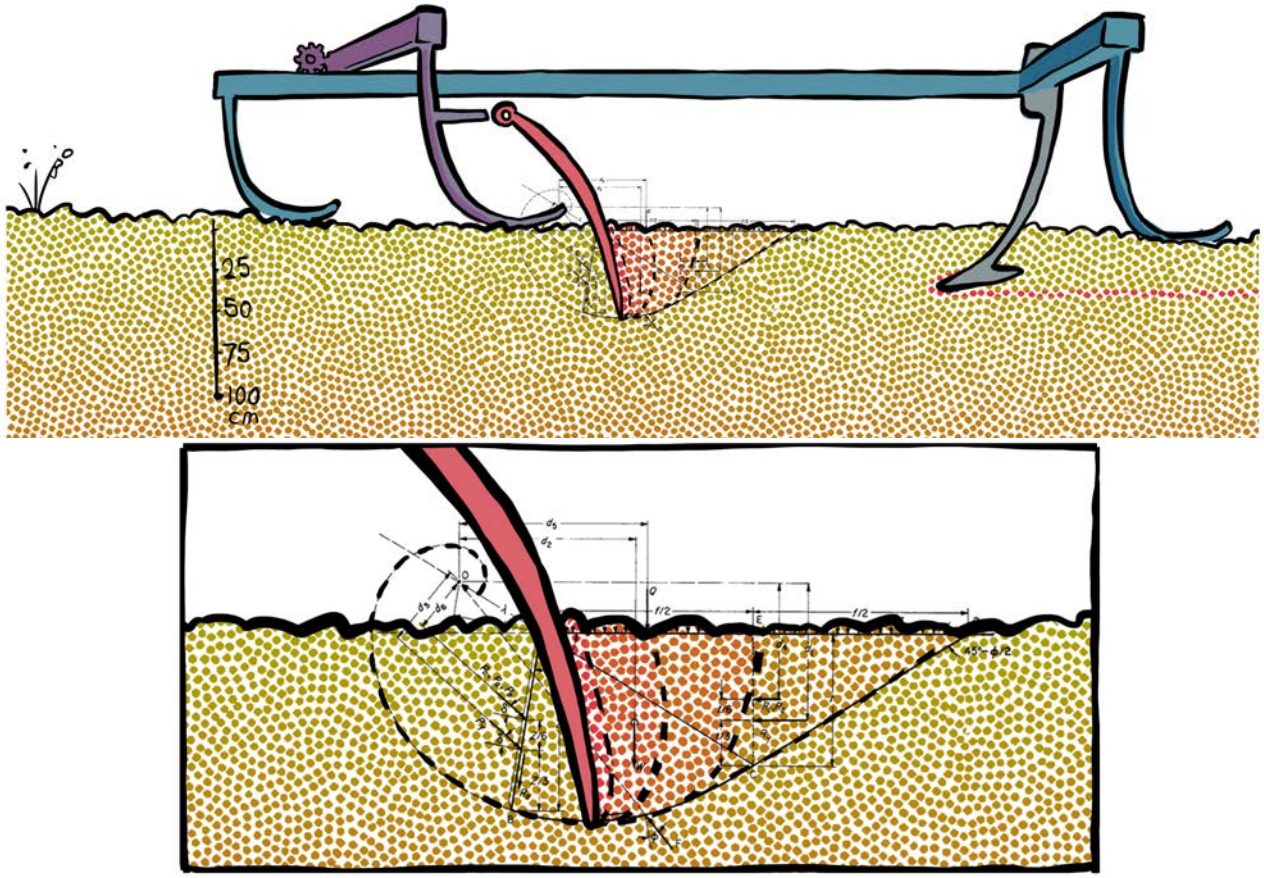

Fig. 4. *A crampon pulls a plow with minimal compaction. In order to pull, crampons only need to press sideways into the soil, avoiding deep compaction. A curved crampon design helps the crampon to penetrate the soil and to reach an angle of close to 90˚ from horizontal in the deeper soil layer, which maximizes soil resistance. The vehicle in this figure moves from right to left and the crampon pushes to the right.*

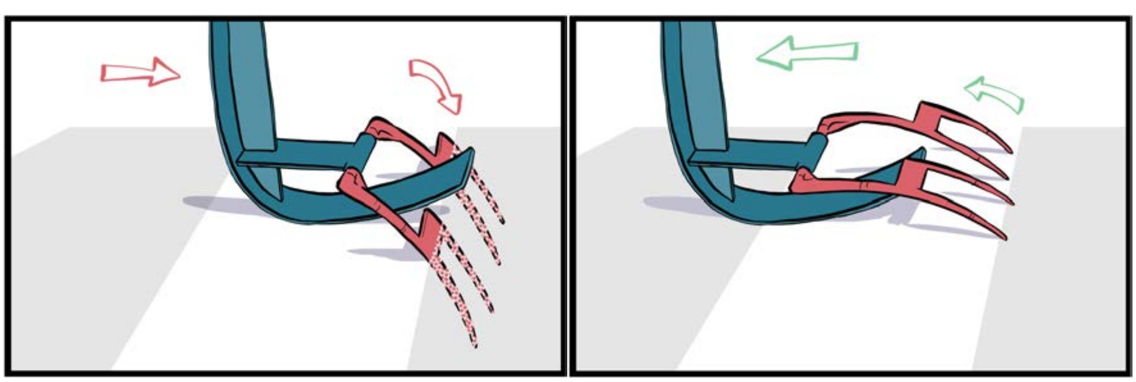

Fig. 5. *Crampon placement can be implemented in a relatively simple way. The vehicle in this figure moves from right to left, such that when a frame is pushed or pulled back, it is moved from left to right.* ***Left:*** *The crampons are pushed into the soil.* ***Right:*** *the crampons are pulled out of the soil as the direction of travel is reversed.*

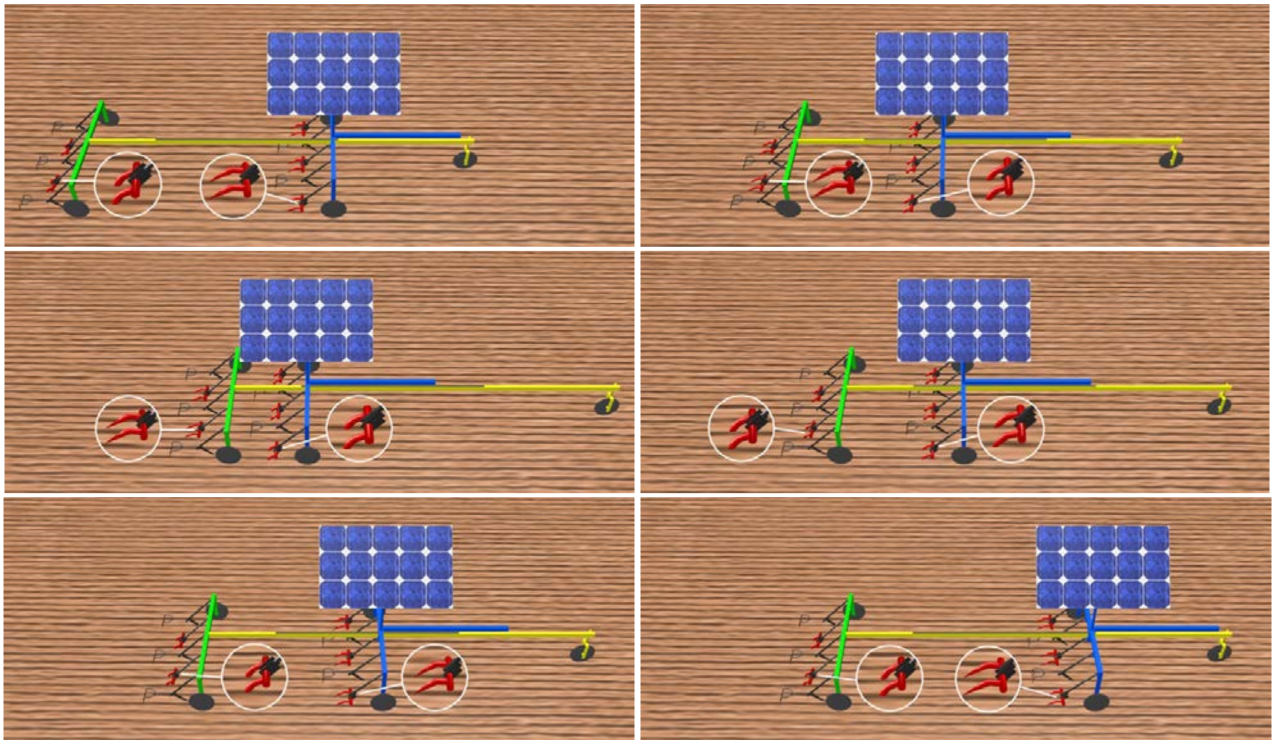

Fig. 6. *Motion pattern of UTOPUS. The crampons on two frames are inserted and extracted from the soil in an alternating push-pull motion pattern. The crampons of one frame are always stable in the soil while the crampons of the other frame move together with its respective frame. The vehicle in this figure moves from left to right.* ***Upper left****: UTOPUS is fully extended. The left set of crampons are anchored in soil and the blue sliding frame is at the fully right position;* ***Upper right****: Right set of crampons are anchored in soil and left tillage tines are being pulled to the right;* ***Middle left****: At the end of the motion shown in upper right image UTOPUS has fully contracted;* ***Middle right****: Left set of crampons are anchored in soil and blue sliding frame with its tillage tines are being pushed to the right;* ***Lower left****: Continuation of motion in middle right image;* ***Lower right****: At the end of the push phase, UTOPUS is fully extended.*

In order to push or pull a device from static crampons, the traction mechanism needs to employ a push-pull mechanism, also known as inching locomotion, an idea which goes back to at least Schreiner and Czako (1973). The simplest push-pull mechanism consists of two independent frames, one behind the other, which are connected by a rigid extensible shaft. Each frame can then be provided with crampons, such that when the front frame is anchored to the ground, the rear frame is pulled forward, and when the rear frame is anchored to the ground, the front frame is pushed forward. See Figure 6 for an illustration of a complete motion cycle of an UTOPUS cultivator.

There is a fundamental difference between the calculation of tractive efficiency of wheeled (or tracked) vehicles and of a push-pull mechanism based on crampons. Wheeled vehicles continuously lose a certain percentage of axle power to tire flexing and tire-soil interaction, and this percentage is largely independent of the size of the tractor. Tractive efficiency of a wheeled tractor can be as high as 80%, but is more often in the region of 70% (Zoz and Grisso, 2003). By contrast, the tractive efficiency of a push-pull vehicle with crampons depends on the length of the shaft of the push-pull mechanism. A crampon needs power to be anchored and de-anchored only once for every alternating phase of the push-pull motion cycle. Once firmly anchored, it will not consume power while the shaft of the push-pull mechanism is further contracted or extended. The authors found that the power needed to anchor and de-anchor the crampons of each frame of a vehicle designed for soil cultivation corresponds to pulling the cultivators for about 12 cm through the soil. With a 4 m long shaft, and a loss of power equivalent to 12 cm of plowing for anchoring and de-anchoring the crampons of each of the two frames, the resulting tractive efficiency is 94%, far better than any wheeled tractor. Even with a 1 m long shaft the tractive efficiency is 76%, which is still competitive.

A crampon generates traction without ballast, which promises a significant reduction in soil compaction. While soil recovery from compaction will take time, natural processes such as shrinking and swelling and biological activity will have the opportunity to work without being compromised by the frequent soil compaction that currently occurs. However, not only the weight of a tractor compacts the soil. Part of the force of a tillage implement is directed downward, below the soil it agitates, and creates a compacted layer of soil which is called the plow pan. This plow pan is of lesser vertical extension than the compaction created by ballasted tractors, yet it still remains an obstacle to root growth. Nambiar and Sands (1992) indicate that if such a compacted layer is perforated at only 0.2% of its area, its inhibition to root growth is largely overcome. The crampons will do exactly this. Since the subsoil below the depth of tillage has more strength, the crampons should be designed such that they penetrate the soil below the depth of tillage. To give an example, for a plowing depth of 15 cm the crampons will likely need to penetrate to a depth of 20 or more, depending on soil properties, thus perforating the plow pan that has formed under the plow.

3. Development of UTOPUS traction technology

Weed control in organic agriculture depends to a large degree on frequent mechanical cultivation before and after sowing and planting. Frequent tractor-powered cultivation damages the soil structure and consumes a large amount of energy, which is neither sustainable nor environmentally friendly. Around 2007 Bover (2011) started to search for an alternative to tractor-based mechanical cultivation which would be suitable to organic agriculture. After initial experiments confirmed that there is no escape from the fundamental fact that wheeled and tracked vehicles can only work efficiently if properly ballasted, the idea of crampon-based traction was first conceived and implemented in early 2010. Figures 7–12 show the development of the UTOPUS traction technology, including designs which have been used in energy autarkic field cultivation with wind and solar energy, different designs for the crampons and the drive train, and a device which can plow to a depth of 20 cm. Videos of the various prototypes at work can be found at http://www.sedewa.com/utopus.html.

Fig. 7: Left: *Experiment to study wheel slip, April 2009.* ***Right***: *Early working prototype, June 2010.*

Fig. 8: ***Left:*** *Improved crampon design, July 2010.* ***Right:*** *Improved stability, September 2010.*

Figure 9: Left*: New experimental design, November 2010.* ***Right****: Solar powered design, January 2011.*

Figure 10: Left*: Improved design of June 2011.* ***Right****: New drive train, October 2011.*

Figure 11: Left*: UTOPUS for deeper tillage (20 cm), March 2012.* ***Right****: Wind powered design, June 2012.*

Figure 12: Left*: Hydraulic drive train, April 2014.* ***Right****: Simplified electric design, November 2014.*

4. Cost and Benefit Calculations

The use of alternative energy sources like solar panels for tillage is not economically viable with current tractor technology, since it is not possible to install enough solar panels on a conventional tractor to provide it with sufficient power for normal operation, nor is there an economically viable solution to store the large amount of energy required by a conventional tractor in onboard batteries. Only a combination of slow robotic automation with energy efficient traction technology will make onboard solar panels economically viable. Automation means that without an expensive human driver the vehicle can be sized down and operated at far lower speeds. Autonomous operation at low speed reduces implement draft and energy consumption per unit area, and allows the work to be spread efficiently over suitable workdays. A commercially successful example is the Husqvarna Autonomous Solar Powered Lawnmower (Husqvarna Group, Stockholm, Sweden), which can double its working time on sunny days.

Because tractors continuously compact soil, they need to plow deeper (primary tillage at least 25 cm) and face a harder soil surface which costs more energy to break open. Before the introduction of soil-compacting tractors it was usually not necessary for primary tillage to plow deeper than 15 cm (King, 1904). A soil management technology which allows a reduction in the depth of primary tillage from 25 cm to 15 cm promises energy savings of 40%. Since tillage implements experience significantly more draft in compacted soil, and if a tractor compacts 33% of topsoil area before tillage, we assume the effect of compaction on draft to be 10%. The high speed (7—8 km/h) of tractors increases draft by another 20%, compared to the 2.5 km/h or less proposed here. The tractive efficiency of tractor tires is 60% to 80% (Zoz et al., 2002; Zoz and Grisso, 2003), which means that tractor tires lose 20% to 40% of axle power to motion resistance and slip. If properly configured, a tillage device which uses crampons loses less than 10%. The cumulative effect of these savings is that slow and light tillage robots with traction based on crampons might well be twice as energy efficient as tractors.

Saving energy while tilling reduces the incentive for farmers to use pesticides and GM crops. This in turn could reduce loss of diversity in crop species and reduce the risk of pesticide resistance. It would also reduce the environmental burden and the occupational hazard associated with pesticides (Hoppin et al. 2007, Hoppin et al. 2009). For the farmer, the long-term benefits of small and light tillage robots are better soil health, high precision soil management, the possibility to maintain a diverse crop rotation in a diverse landscape, reduced pesticide exposure, and more possibilities for organic farming. These benefits promise reduced crop inputs, higher yields, and better health. However, adoption often depends on short term benefits, and these are: reduced fuel consumption, lower operating costs, and a more comfortable work pattern. Table 1 provides a simple cost-benefit analysis of tillage cost per hectare, based on a common tillage pattern: one primary tillage operation, two secondary tillage operations to incorporate fertilizers, loosen the soil, and prepare the seedbed, and two operations of row cultivation for weed control after planting. Depending on the crop, these operations constitute between 20% and 40% of total work and machine costs per hectare per year.

To calculate the economic competitiveness of a small autonomous tillage robot with anchor traction, the authors consider a target sale price of at 7,500 euro in Europe, including tools, but excluding batteries and solar panels. The target cost of maintenance and repairs over a standard 12-year deprecation period is 6,000 euro. A solar panel of 1 kW nominal power and a solar tracker can be installed for 1,500 euro. Assuming a daily work output of 3.2 kWh and 100 work days per year, the machine can then continuously maintain 12 hectares of land, at a machine cost of 4 euro/kWh. The only fuel cost is for a weekly field visit for control and (re)deployment, which the authors estimate to include 15 minutes of driving to the field and 30 minutes of field work. If the robot is charged from the electric grid, the work output during daytime can be 6.5 kWh per day for 100 work days a year, and the machine can maintain 25 ha of land at a machine cost of 1.75 euro/kWh, plus 0.5 euro/kWh for battery deprecation and grid electricity, see Table 1 for a back-of-the-envelope calculation of costs and benefits.

While the world market for agricultural machinery is 90 billion euro (Wiesendorfer et al., 2014), the world market for agricultural robots is still small. Figures differ significantly. A recent estimate by WinterGreen Research Inc. (2014) values the agricultural robot market at 817 million US$ in 2013 and predicts a “hefty growth for a nascent market” and a market volume of 16,000 million US$ in 2020. This trend is likely to continue and autonomous robotic devices are poised to become ubiquitous in the coming years. Current market studies already show a high diversity in development of prototypes and in professionally distributed and sold products. Commercially successful agricultural robots range from livestock guarding robots to special crop harvesters. Some robots are dedicated to particular tasks or crops, e.g., the AGROBOT which is devoted to strawberry harvesting (AGROBOT, Oxnard, California, USA), while other robots provide common platforms for a variety of tasks, e.g., BoniRob as a versatile platform to mount electric and hydraulic manipulation tools (Amanzone, Bonn, Germany). The Oz Weeding Robot is a successful commercial product which is powered by a standard car battery and which is capable of fully autonomous weeding operations in open fields and greenhouses (Naïo Technologies, Toulouse, France).

A broad range of patents on agricultural robots has been published showing innovation hotspots in China, Japan, Korea and the United States. While a detailed overview is beyond the scope of this article, we note that the reduction of energy cost is a central topic of many of these inventions. As far as we have determined only one group is developing a fully energy autarkic solution: the Ladybird agricultural prototype robot which is being designed and developed by the Australian Centre for Field Robotics, University of Sydney, Australia. The aspect of compaction is sometimes mentioned in the context of a certain development but never—as far as we have seen—a prominent argument in favor of a certain innovation. In view of this innovative activity, UTOPUS has one unique characteristic which sets it apart: its crampon-based traction technology which aims from the very beginning to minimize soil compaction.

Table 1: Cost-benefit analysis of robot with crampons and of conventional tractor. Numbers are per hectare**.** Price calculations are in Euro. Source: Achilles et al. (2010); ASABE (2006); Frisch et al. (2014); Hanna (2014); Schnitkey (2012).

	Solar robot with crampons	**Electric grid robot with crampons**	**Conventional tractor**
Costs			
Primary tillage	14 cm deep chisel, 56 euro machine costs (14 kWh)	14 cm deep chisel, 31.5 euro machine costs (14 kWh)	25 cm deep chisel, 1.1 hours work, 33 euro machine costs (67 kW tractor, 15 L diesel)
Secondary tillage (two rounds)	7 cm deep chisel, 36 euro machine costs (9 kWh)	7 cm deep chisel, 22.5 euro machine costs (9 kWh)	15 & 7 cm deep chisel, 1.7 hours work, 50 euro machine costs (67 kW tractor, 18 L diesel)
Row cultivation (two rounds)	3 cm deep duck foot, 12 euro machine costs (3 kWh)	3 cm deep duck foot, 7.5 euro machine costs (3 kWh)	4.5 cm deep duck foot, 1.5 hours work, 22 euro machine costs (45 kW tractor, 8 L diesel)
Robot super-vision and maintenance, once a week	1 hour work, 1 euro machine costs (0.5 L diesel)	0.5 hour work, 0.5 euro machine costs (0.25 L diesel)	
Total Costs / hectare	**1 hour work, 105 euro machine costs (including 26 kWh, 0.5 L diesel)**	**0.5 hour work, 59 euro machine costs (including 26 kWh, 0.25 L diesel)**	**4.3 hours work, 105 euro machine costs (including 41 L diesel + oil)**
Benefits			
Weed control	Yes	Yes	Yes
Healthy topsoil	Yes	Yes	Yes
Healthy subsoil	Yes	Yes	No (compacted)
Reduced greenhouse gas emissions	Yes (0.5 L diesel)	Yes (0.25 L diesel)	No (41 L diesel)

5. Conclusion

Increasing population pressure on the limited amount of fertile soil requires new farming methods which maximize soil fertility and crop yield. This includes intensification of soil and plant management by autonomous robots, while at the same time minimizing soil degradation due to vehicle traffic on agricultural soil. The present article identifies ballasted wheels or tracks as a dominant reason for vehicle induced soil degradation, and introduces UTOPUS, a new traction technology based on push-pull locomotion and retractable crampons which utilize subsoil strength to generate push or pull. By placing narrow crampons with a hinge to the back of a moving frame, the crampons can be rotated into the soil in a self-regulating manner, such that the anchoring process minimizes energy consumption and disturbance of the subsoil. As the crampons require no ballast and press only sideways into the soil, they are expected to minimize many of the damaging effects to soil which are associated with wheeled and tracked tractors.

We have tested several different prototypes and found that the principle permits a broad range of design options for the crampons, the drive train, and the energy supply. We also found that energy autarkic soil cultivation powered by solar and even wind is possible. Our cost-benefit analysis shows that UTOPUS traction technology might be economically competitive if integrated into an autonomic robotic solution, several of which are under active scientific and commercial development around the world.

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