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REVIEW

Improving On-farm Energy Use Efficiency by Optimizing Machinery Operations and Management: A Review

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Abstract

The energy use and emissions from direct fossil fuel combustion on-farms to power farm machinery was critically reviewed. Approximately, 15% of agricultural production costs on-farm are energy-related. A potential solution to more sustainable energy use is a shift toward biofuels from renewable resources. The reduction of greenhouse gas emissions through the substitution of diesel oil with biodiesel depends on the feedstock, the inter-esterification process, the storage period, and ambient conditions. In modern tractors, increased fuel use efficiency (or reduced fuel consumption) has been achieved by power/load matching and the use of variable transmission. Engine management systems that are capable of continuously communicating with the engine and transmission to make appropriate adjustments based on inputs received from the tractor allow for quick and precise responses to changing conditions. As a result, maximum efficiency and productivity can be obtained from the tractor operating similarly to the traditional 'gear-up and throttle-back' methods of a proficient operator. The future for autonomous tractors is promising, though not new. Electric-powered tractors are near to commercialization or are already commercially available. Hybrid electric driven tractors present some advantages in terms of increased energy use efficiency and functionalities. Increased efficiency can lead to a reduction in diesel fuel consumption and hence, a concurrent decrease in CO_2 emission. Where the local electricity supply has a low-carbon emission factor, this can also result in significant emission reductions. Small light-weight robotic equipment can potentially perform functions currently undertaken by tractor-drawn and other heavy equipment with high-fuel consumption, provided field operating capacity was not compromised. However, the size and weight limitations inherent in current harvesting and transport technology mean that soil compaction will still be a problem with robotic units. The robotic operation of medium-scale equipment within a precision-controlled traffic farming environment should offer more feasible and energy-efficient alternatives.

Keywords Controlled traffic farming · Embodied energy · Greenhouse gas emissions · No-tillage · Soil compaction · Rolling resistance

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Introduction

It has been estimated that approximately 15% of agricultural production costs on-farm are energy related [81]. Using existing energy sources more efficiently and greater adoption of renewable forms of energy at the farm-scale can both save costs and reduce greenhouse gas (GHG) emissions. Efforts to measure and reduce energy use can be traced back to the 'oil shocks' of the 1970s and early 1980s, which saw significant increases in prices, and in some regions, supply shortages, resulting partly from actions by members of the Organization of Petroleum Exporting Countries (OPEC) [47]. In more recent times, concerns about GHG emissions and their contribution to global warming and climate change, as exemplified by the 2015 Paris Climate Agreement and the 2021 Glasgow Climate Pact, have motivated many national and local governments, and agricultural organizations to examine the means of reducing such emissions. Global energy demand is the principal contributor to the anthropogenic release of GHGs, particularly carbon dioxide (CO_2), to the atmosphere.

Global warming and climate change caused by GHG emissions are strongly linked to fossil energy production and utilization [39]. The global food supply chain is responsible for around one-third of end use energy consumption and a quarter of total GHG emissions [24]. Most mechanized farms depend on diesel fuel to run tractors, farm vehicles, harvesters, and other farm equipment. Fossil fuels are the main energy costs for arable farm operations representing up to 75% of the total energy spent on modern industrial-scale farms, depending on the cropping system [96]. Small-scale and subsistence farms in developing countries have traditionally relied on animal traction and human labor, including for transport of products to markets, and hence have been less dependent on fossil fuel inputs. However, recent developments in mechanization for smallholder systems and mechanization adoption has increased the demand for fuel in those systems [10]. Cutting fuel costs can be relatively simple, starting with operating machinery in a smarter manner; for example, by correctly setting up and maintaining vehicles and equipment, and developing a fuel management plan. As an example, US research has shown that the basic practice of maintaining clean fuel and air filters can save around 380 L ($\sim$ 100 US gallons) of diesel fuel annually. Buying more fuel-efficient vehicles can also result in significant fuel savings, which may be considered as part of the machinery replacement program [41].

A review of past and recent research was undertaken to identify ways of reducing energy-related costs and environmental impacts associated with the operation of farm machinery and on-farm energy use. Indirect energy use (e.g., use of fossil fuels in manufacturing inputs such as animal feed or fertilizer) is briefly covered in this analysis, however, other on-farm energy uses such as for heating or ventilation of buildings and other sources of GHG emissions (e.g., biogenic methane from ruminant livestock, nitrous oxide emissions arising from animal manure and nitrogen fertilizer use) are not discussed. The work reflects, primarily, an Australian perspective, but it draws from relevant evidence reported elsewhere. The highly mechanized Australian agricultural systems resemble large-holder (arable) enterprises found in other parts of the world, particularly the USA, Canada, Brazil, and Argentina [64]. Hence, the analysis presented here is also relevant to those systems. Therefore, a key focus of this review was to critically discuss energy use and emissions from direct fossil fuel combustion on farms to power farm machinery, specifically tractors. On-farm energy use and energy use efficiency in small-holder agriculture settings were considered to be outside the scope of this work and as such they merit a separate analysis. Hence, it is recommended that this work is expanded by undertaking a similar review analysis relevant to small landholder farming systems.

Techniques for Optimizing Tractor Fuel Consumption

Adaptive Driving: Gear-up and Throttle-back

Gear-up and throttle-back (GUTB) is a fuel-saving practice that has been popular around the world since the fuel crisis of the mid-1970s. The GUTB technique can be implemented to save fuel when drawbar loads are light ($<$ 75% of rated power) and power take-off (PTO) speed can be reduced [34]. This method improves engine efficiency by maintaining high engine load and an engine speed at 60–80% of rated speed [35]. Significant improvements in fuel and tractive efficiency from implementation of this method were achieved with two- and four-wheel drive tractors in Canada [69]. For maximum operating efficiency, a tractor engine should be operated near its rated capacity. Many field operations such as light tillage, planting, mechanical weed control, spraying, and hay-raking, however, do not require full tractor power. This is particularly true when older implements that were sized for smaller tractors are used with today's high-horsepower tractors or existing tractors are used in controlled traffic farming (CTF) and no-tillage operations, where power requirements are much lower. Many operations require fixed ground speeds. For these lighter operations, substantial fuel savings are possible by operating the tractor on a higher gear and lower engine speed, while maintaining the desired field speed. The GUTB method will not suit all tractor operations. Certain PTO operated implements require high engine speeds for the correct operation of the equipment and, as such, their use is incompatible with the GUTB method. When evaluating options for a new tractor purchase, it is recommended to clarify how energy efficiency can be optimized for PTO applications and how the PTO affects general engine efficiency. The most basic efficiency measure is to avoid overloading the engine by using a gear that is too high for the task. Adaptive driving depends on the operator receiving accurate feedback on both engine performance and driver performance. Depending on the age and capabilities of the tractor, the key sources of data are:

- In-cab, real-time monitoring of engine performance, and
- Learning the specific signals that indicate the limits of engine speed reduction possible for a given gearing and load (engine sound can be misleading, so black smoke coming from the exhaust is also a good indicator, as is lack of engine speed response to an increase in throttle setting).

Optimizing Tire Inflation Pressure

Tires should always be inflated to the manufacturer's recommended inflation pressure for a given load, speed, and surface conditions (ground carrying capacity and slope). When carrying a load over a firm or hard surface the tire deflects, causing an increase of the contact patch area until the load can be supported without further deformation of the tire. A loaded tire is deflected near the contact patch and is continuously flexed as it rolls along. For most agricultural tires, the maximum deflection is limited to about 18–20% of the section height, to prevent damage inflicted on the carcass (the casing of the tire). With an increasing load on the tire, the inflation pressure must be raised to maintain acceptable deflections, avoid damage to the tire and for safety reasons. In soft (off-road) conditions, the soil deforms to allow for increased contact patch area, thus reducing the deflection of the tire for a given load and inflation pressure [3]. Hence, in softer soil conditions, the tire inflation pressure may be reduced compared with the recommended pressure for the same load on a firmer surface. Central tire inflation systems (CTIS) offer advantages for 'quick' adjustments of the tires inflation pressure for improved traction, reduced slip and tire wear, and increased tire-soil contact area (equally, reduced soil-tire contact pressure). Such adjustments may help to reduce rolling resistance, that is the pull required to move a wheel across a horizontal surface [2], and improve fuel use efficiency depending on specific ground conditions, but the recommended tire inflation pressure must be restored for firmer surface use. Rolling resistance increases almost proportionally to the increase in load which the tire is supporting. The rolling resistance has two main components [50]:

- The internal rolling resistance, which is caused by the loss of energy resulting from the continuous flexing of the tire's carcass as the wheel rotates in contact with the ground, and
- The external rolling resistance, which arises from the energy that the wheel must expend in deforming the soil surface.

In off-road conditions, the rolling resistance caused by soil deformation is about 5 times greater (or more) than the internal resistance, depending upon the tire construction. A rut formed by the pass of a wheel over the soil (Fig. 1) is evidence of the expenditure of energy in deforming that soil, and in general, the larger the cross-section of the tire rut, the greater the rolling resistance [74]. Rolling resistance, slip and compaction may be reduced by using power by traveling at higher speeds, and by increasing the contact area and reducing weight. If weight cannot be reduced, an increase in the contact area will reduce the soil-tire contact pressure. A reduction in the contact pressure can be achieved by increasing the tire diameter, the section width or both (although the former is preferable to keep rolling resistance low), operating the tire at the minimum allowable (safe) inflation pressure or fitting dual tires at low inflation pressure, and where possible, using repeated wheeling [63]. An increase in contact area through increased tire diameter is preferable to tire section width because it will minimize rut width and reduce rolling resistance [5, 52]. Increased contact area between the soil and the tire will reduce tire slip and therefore rolling resistance [51]. The correct tire inflation pressure inflation is determined by the tire size, tire construction characteristics, load carried by the tire and traveling speed, and it can be obtained from the tire manufacturer's website or the tractor's operating manual.

Wheel Slip and Tractor Ballasting

Most tractor operators know that proper ballasting is important to transfer as much engine power as possible to the drawbar. Exactly how to accomplish this ballasting, however, frequently remains a mystery. Too little ballast or weight can result in excessive slippage of the drive-wheels and hence an obvious waste of fuel. Conversely, carrying too much ballast on a tractor dramatically lowers wheel slip but results in greater rolling resistance as the tractor sinks too far into the soil, causing wheels to be constantly climbing out of a deep rut [37]. Often, large modern

Fig. 1 Large rutting caused by a cotton picker while harvesting on soft soil in 2024 near Griffith (New South Wales, Australia). The cotton picker was fitted with dual tires (520/85R42-R1, average wheel load: 5.43 Mg, inflation pressure: 2.5 bar) on the front axle and single tires (520/85R34-R1, average wheel load: 8.25 Mg, inflation pressure: 3.2 bar) on the rear axle. At the time of traffic, the soil was near drained upper limit ($\sim$ 100 cm suction) and had a soil water content of $\sim$ 24% (by weight). The maximum rut depth, measured at the centerline of the tire rut, ranged between 370 and 560 mm. Source: Dr Diogenes L. Antille (CSIRO Agriculture and Food, with permission)

Table 1 Gross tractor weight for a range of tractors operated at varying forward speeds (after Hanna et al. [37])

Tractor type	Forward speed, km h^{-1}		
–	< 7.0	8.0	> 9.0
–	Gross tractor weight, kg kW^{-1}		
Two-wheel drive (2WD) or front-wheel drive (FWD)	80	73	67
Four-wheel drive (4WD)	67	61	65

tractors have an option to display wheel slippage on the instrument panel for the operator. To maximize the transfer of power from drive axles to the drawbar, optimum amounts of wheel slippage depend on the soil surface. On firm, untilled soil, wheel slip should be in a range of about 6–13%. Higher slippage of 8–16%, is acceptable on a tilled surface with slightly more on a noncohesive sandy soil. Conversely, on concrete or tar seal surfaces, optimal wheel slip is about 4–8%. Checking wheel slippage on tractors equipped to display this information makes it easy to check to determine if the tractor is optimally applying power to the drawbar and therefore using fuel efficiently. If tractor wheel slip is outside suggested ranges for operation with drawbar loads, check the operator's manual for ballasting suggestions. Table 1 also provides guidance on gross tractor weights. The total gross tractor weight required for optimal ballasting is a function of tractor type (two-wheel drive [2WD], mechanical front-wheel assist [FWA] drive, four-wheel drive [4WD]), and travel speed in the field [51]. Since only wheels on powered axles supply traction, it is important to distribute ballast properly between the front and rear axles. The optimal weight on each axle is affected by tractor style and whether the attached implement is pulled or mounted (Table 2).

Equipment such as manure tank wagons and grain carts have significant tongue weight on the drawbar and can be considered 'fully mounted' loads when calculating the proper weight split between front and rear axles because they add weight to the tractor's rear axle similar to fully mounted implements. An important exception to this ballasting procedure occurs when lighter drawbar loads are used that require less than half of the available tractor

Table 2 Front-to-rear axle load ratios expressed as a percentage of total tractor weight for three different tractor types (after Hanna et al. [37])

Tractor type	Towed/drawbar	Semi-mounted	Fully mounted
Two-wheel drive (2WD)	25/75	30/70	35/65
Front-wheel drive (FWA)	35/65	35/65	40/60
Four-wheel drive (4WD)	55/45	55/45	60/40

power. Examples include a pull-behind sprayer, a small planter, or a field cultivator that does not require much power. Ballast previously added for primary tillage or heavy drawbar loads simply adds to tractor weight, increases rolling resistance, and can increase fuel use.

Although adding and removing cast iron ballast as wheel weights or front weights can be daunting, it is necessary for optimum performance. Ballast needs to be removed for lighter drawbar work, such as planting and spraying and added to the tractor prior to heavy tillage operations which require more of the tractor's engine power to be transferred to the drawbar. Optimum total tractor weights and percentage weight-splits between the front and rear axles are shown in Tables 1 and 2 as a guide. Because tractor fuel and power efficiency are optimized over a range of wheel slippages, fuel use is not likely to increase substantially with a 5% deviation from these values. However, increased fuel use may become evident if weights differ by 10% or more. Incorrect ballasting can have a substantial negative effect on fuel use efficiency and on tractor performance overall. When the ballast is set around the right range, little fuel-efficiency benefit can be achieved from constantly tweaking ballast to compensate for different soil conditions or to allow for variations in the weight of mounted equipment [31]. If wheel slip cannot be easily controlled and tractor axle weights are not known, they should be measured to gain confidence that fuel is not being wasted. Total tractor weight as well as the weight being carried on each axle (Table 2) can be determined by a weigh bridge on the farm, use of a public weigh bridge, or using portable scales under each wheel. There are two common ways to add ballast to a tractor: attaching cast-iron weights or filling the tires with fluid. Cast weights can be more expensive but make it easier to quickly adjust ballast to suit changing conditions. Adding fluid to the front tires on a FWD tractor is an efficient method for adding ballast to the front axle when needed and controlling power-hop without exceeding the optimum inflation pressure. Power-hop is a bouncing effect that a tractor can experience in the field when pulling a load and it occurs when the stiffness of the tires matches the natural frequency of the tractor. Power-hop may be caused by improper ballasting (improper front and rear weight distribution) and improperly inflated tires. When fluid is added to the tires on the rear axle, exceeding 75% fill should be avoided. All tires on the same axle should be filled to the same level [80]. The additional weight from adding dual wheels to gain traction under soft soil conditions should be considered as ballast on the rear axle. Dual tires are typically used when a second wheel is required to support axle weight or to improve flotation or stability, and enhance traction on cohesive soil (increased soil-tire contact area). Dual tires can also decrease rolling resistance or improve traction if soil conditions are soft or marginal [44]. Unpowered front wheels on a 2WD tractor are necessary for steering control but do not help tractive propulsion, although some 2WD models offer optional FWD so that they help pull the load rather than simply creating rolling resistance when being passively pushed through the soil [75]. To create traction, the peripheral speed of lugs on the front wheels are slightly faster than those on rear tires. To prevent extra wear on the drive transmission, manufacturers sometimes recommend disengaging FWD during road travel when added traction may not be beneficial.

Estimating Fuel Requirements

Fuel consumption for most tillage operations is directly related to tillage depth [17, 33]. The goal of any tillage operation should be to set the correct depth rather than simply pulling the implement as deeply as the tractor's power will allow. Travel speed affects the time required to complete a given field operation and will impact on field efficiency and timeliness. In most cases, farmers choose to accomplish work as quickly as possible, so reducing field speed is not an appealing option. Although a tractor's speed of operation impacts on energy use, in some cases fuel consumption may only be marginally impacted, such as when reduced engine speed and a higher gear is used for faster travel speed. Fuel consumption may occasionally decrease with faster tillage speed if small changes in drawbar load are balanced by operating the tractor engine at a more fuel-efficient combination of greater torque and lower engine speed [83].

Transitioning to Fuel-Efficient Tractors

When upgrading to a new tractor, the manufacturers' claims of fuel consumption should be compared, for example, with data issued by The Nebraska Tractor Test Laboratory (https://tractortestlab.unl.edu/), and the aim to minimize overall fuel consumption over the life of the tractor [49]. However, the real measure of fuel use efficiency should be liters per hectare and not liters per hour [77]. Fuel consumption is a combination of engine, tractor (importantly, transmission), implement design, and operator performance [42, 87]. Using less fuel per hour but taking more time to complete a task (whether due to the machine operator or unplanned field trajectories) may mean that optimum fuel savings are not being achieved [14]. Field trajectories must be optimized to ensure travel distance, and therefore in-field time, is minimized according to the operation being performed [16]. Machinery operations conducted in fields managed under controlled traffic are often more efficiently performed than in noncontrolled or randomly managed systems [7, 15].

Developments in Fuel-Efficient Tractor Designs

Power/load Matching

Major tractor manufacturers have adopted power/load matching methods that are indicated by a range of acronyms (e.g., IVT CVT) but offer the same functionality. For example, Howard et al. [41] compared a John Deere 8295R infinitely variable transmission (IVT) tractor with a John Deere 8295R Power-shift transmission (PST) with continuously-variable transmission (CVT). When shifting up two gears and throttling back, they found fuel consumption was linearly related to drawbar power. Such a relationship alternated between the PST being more economical at lower loads (< 52% maximum load) with the CVT being more efficient above that level. The John Deere IVT provides a seamless range of speeds, and no clutching is required to start or stop the tractor. The IVT has a fully integrated electronic management system (EMS) that allows the engine to communicate 100 times a second with the transmission. Electronic communication and interaction between the engine and the transmission enable optimum productivity and efficiency at any engine speed. This can be achieved because the operating conditions are being constantly monitored and relayed to the EMS which then automatically determines whether the tractor is in a near fully loaded condition or a light- to no-load condition. It then makes the appropriate adjustments accordingly. The EMS works with the IVT transmission and engine to maintain the selected travel speed at reduced engine speed (RPM) when the IVT selector activates the system. This results in increased efficiency and reduced fuel consumption. There are generally several 'mode settings' as outlined below:

- Off-operator selects the engine speed and ground speed (EMS is turned off and so the operator sets the engine and ground speed as if driving the tractor with no management systems).
- Primarily for PTO-powered applications, the engine speed can only be reduced minimally to maintain the correct standard PTO operating speed (of either 540 or 1000 RPM). When a load from an implement is placed on the tractor, the engine will first increase power to maintain PTO RPM. Once maximum engine power is reached and additional load is placed on the tractor, the IVT transmission will reduce forward speed enough to keep the tractor's engine at around maximum power output level until the tougher conditions have passed. Then the transmission will increase the forward speed back up to the required speed as selected. Once the load is reduced further, engine speed will again drop automatically to reduce fuel consumption. All of this is done through the EMS ensuring communication between the engine and the transmission.
- For heavy draught and tillage applications, or when hydraulic oil flow is needed, the tractor will try to maintain the selected ground speed at reduced engine speed for improved efficiency and reduced fuel consumption. The minimum engine speed is adjusted by the CommandCenter™ to customize the tractor to the specific application (the CommandCenter™ is a display system that, tied with a position receiver, provides the power needed to perform all the tractor's agricultural features and functions). Since the power takeoff (PTO) is no longer involved, the speed is allowed to go lower than when powering an implement through the PTO. When the load increases on the tractor, the engine increases power until maximum power is reached, then, if needed, the IVT transmission will ratio down (to slow the tractor forward speed) enough to keep engine power at maximum. Once the tractor has passed through this tougher area of the paddock, the IVT will ratio up (and hence increase forward speed) back to the selected speed and the engine will reduce RPM speed. All these operations are performed automatically by the EMS.
- For transport and light tillage applications, the engine speed will reduce compared to either the PTO or heavy draught operations to save additional fuel. A tractor is typically capable of a full transport road speed of around 40 km h^{-1} at very low engine speed (sometimes as low as 1200 RPM). As with the John Deere 8295R example, the minimum engine speed is adjustable by the CommandCenter™, which allows the operator to customize the tractor performance to suit the application.

In the above example, the EMS operates similarly to the traditional 'gear-up and throttle-back' operation that can be performed manually by good operators. However, because the EMS continuously communicates with the engine and transmission, making appropriate adjustments based on inputs received from the tractor, it responds quickly and precisely to changing conditions. This allows maximum efficiency and productivity to be obtained from the tractor. Given that the changes are automatic, the system reduces the reliance on operator experience to make the appropriate manual adjustments at the correct time.

Fuel Injection and Exhaust Aftertreatment Systems

Traditional diesel engines used in tractors have a mechanical injection system. Recent developments such as high-pressure and electronically controlled fuel systems are being increasingly installed by manufacturers. High-pressure injection systems operate at a pump pressure of around 1500 bar compared with 240 bar for traditional designs. The injection pump transfers the fuel to a high-pressure line known as the "common rail", where each fuel injection unit is opened by pressure [79]. The use of high-pressure injection systems allows changes in the injection time, the opening pressure of the injection unit and the fuel injection point [40], which leads to improved use efficiency and emission control [11]. It also enables the use of alternative biofuels, with engine performance being maintained using different fuel compositions and blends. Electronically controlled injection systems have enabled the development of injection strategies based on engine sensors. Electronically controlled sensors regulate the angular speed of the crankshaft and the position of the accelerator. These sensors transmit information on these parameters to the electronic control unit (ECU) which varies the amount of fuel injected to meet the load. In addition, sensors at air and fuel inlets monitor possible obstructions and engine temperature, which enables current emission standards, such as the US Environmental Protection Agency (EPA) Tier 2/3/4/5 standards (North America) and EURO standards (Europe), to be met. Through advances in design, modern diesel engines have been transformed into one of the cleanest prime moving systems available today. These engine improvements include high-pressure common rail fuel injection systems, electronically controlled injector solenoids and advanced turbocharging. Manufacturers can meet emissions standards by adjusting the electronically controlled high-pressure injection system [68]. While these improvements have enabled engine manufacturers to meet Tier 2 and Tier 3 emissions standards, to meet the more stringent Tier 4 and Tier 5 standards, exhaust aftertreatment is also required. The main technologies used for exhaust aftertreatment are as follows:

- Selective catalytic reduction (SCR), which combines the exhaust gases with ammonia (urea or diesel emissions fluid [DEF]) and passes this mixture over a catalyst. Roughly 1 L of DEF is required to treat emissions from 20 L of diesel fuel.
- Diesel particulate filter (DPF), which uses a mechanical filter to trap soot particles after they have been partially oxidized by a catalyst. At certain intervals during operation, the trapped particles are incinerated.
- Exhaust gas recirculation (EGR), which allows a small amount of cooled exhaust gas to be recirculated back into the combustion chamber. This process reduces the combustion temperature and the production of NO_x. However, EGR increases particulate emissions, so a DPF will also be needed to meet Tier 4 final regulations.

Tier 4 emissions legislation is leading to widespread adoption of exhaust aftertreatment in off-highway applications for engines with power greater than 18 kW (24 HP). Manufacturers of large engines are faced with the significant challenge of packaging a multitude of catalyst technologies into existing designs, contending with the fuel consumption consequences of the increased back pressure/higher operating temperature/greater cooling requirement, as well as dealing with the incremental cost and weight associated with aftertreatment equipment [86].

Measuring Tractor Performance

Interest in data to monitor the in-field performance of an agricultural tractor is not a new topic. In the late 1990s transducers were mounted on tractors to measure operational parameters such as engine performance, wheel and ground speeds with additional devices used to measure fuel consumption [43]. Modern tractors now have a performance-monitoring system that provides real-time fuel consumption, engine and ground speed, and wheel slip with telemetry enabling data to be transmitted and stored for future reference. Real-time data can be analyzed to give immediate feedback to assess different machine settings and configurations as well as operator performance [1]. Recent advances in data processing and exchange (e.g., CAN Standard ISO-11898) as well as developments such as Real-Time Kinematic (RTK) global positioning systems which allow for more precise tracking, also allows for comparisons and benchmarking of machines undertaking similar tasks. An example of the use of such data is tractor tests completed as part of detailed on-farm energy assessments conducted by Foley et al. [25]. The tests were conducted on the black-cracking clay soils of a large, irrigated cotton farm in the Darling Downs region of Queensland

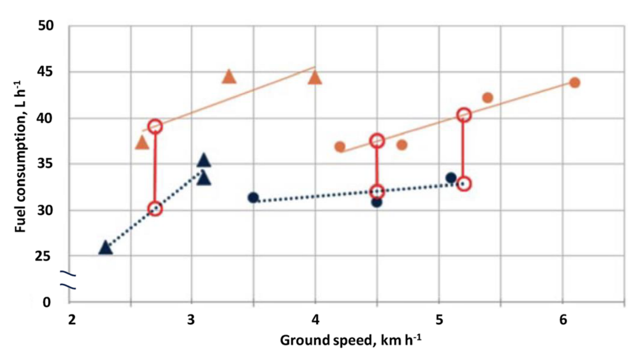

Fig. 2 Fuel consumption as a function of ground speed for a John Deere 8220 (168 kW or 225 HP) tractor. The tractor was operated at two different engine speeds: 2300 RPM (orange solid lines) and 1830 RPM (dark dotted lines), and two different ripping depths: 350 mm (triangles) and 250 mm (solid circles), respectively (after Foley et al. [25], with permission)

(Australia), using a 4.5 m wide fixed-tine ripper behind a 2010 John Deere 8220 tractor. The tractor's 8.1 L engine was electronically controlled and turbocharged to give a rated power of 225 kW (168 HP). For the trial, the tractor was put through a series of tillage runs at varying depths and across a range of engine speeds and gear selections to compare ground speed and fuel consumption. Hourly fuel consumption rates varied at two ripping depths as a result of changing engine speed and gear selection (Fig. 2). Reducing the engine speed of the tractor reduced fuel use by between 6 and 9 L h^{-1} across three selected pairs of equal ground speed and ripping depths (shown by the red circles and bars in Fig. 2) with an average reduction of 7 L h^{-1}. This confirmed that throttling back and gearing up reduces fuel consumption.

For a heavy tillage operation, at a work rate of around 2 ha h^{-1} and a working depth of 250 mm, shifting gears from fifth up to seventh, and throttling back the engine speed from 2300 to 1830 RPM, reduced fuel consumption by 6.7 L h^{-1} while maintaining the same ground speed and work rate. On a per hectare basis, this equated to a reduction in fuel use of 3.6 L ha^{-1}, or about 20%, which represented a reduction of 0.14 GJ of energy per ha and 10 kg CO_2 per ha emissions. Tests also showed that, for every 25 mm increase in the depth of heavy tillage, tractor fuel consumption increased by 2 L ha^{-1}. A 10% reduction in fuel costs and emissions per ha was achieved when tillage depth was reduced by 25 mm [25].

Energy Effects of Farming Systems: No-tillage and Controlled Traffic Farming

Tillage has been the basis of most farming systems for more than 10,000 years [53]. It is the traditional way to control weeds, incorporate crop residue, relieve compaction, and prepare a seedbed prior to crop establishment. Tillage is energy intensive and therefore expensive, and it may accelerate soil water loss and leave the soil vulnerable to erosion by wind or water. When effective herbicides appeared in the 1960s, no-tillage cropping research and development followed rapidly. On-farm adoption was much slower, as farmers and (often small) machinery makers worked to develop and adapt equipment and systems for no-tillage cropping. Zero-tillage is a generic term, which precludes any pre-seeding tillage, but includes mechanization systems that rely on the use of tine seeders (e.g., wide-tine or knife types), and minimal-disturbance disc seeders (the latter sometimes referred to as no-tillage). The economic and environmental costs of tillage ensured that its role was questioned in almost all cropping systems. In more humid environments (e.g., northern Europe) issues of managing high residue loads have slowed adoption, but there is ongoing farmer interest in no-tillage, and a widespread move towards reduced tillage systems [85]. The advantages of no-tillage were clearest in more arid and erosion-prone environments, such as Australia, where almost 85% of grain production is under no-tillage [92]. Soil nutrient stratification and soil compaction can create issues for long-term no-tillage farming in some situations [23], but the development of herbicide-tolerant weeds is becoming a major problem in most environments. Current resistance management strategies include crop and herbicide group rotation, improving crop competition, reducing weed seed set and harvest weed seed control. In the longer term, the development of sensor technologies such as optical weed recognition could be important contributors to resistance management. On-farm energy costs are clearly reduced by no-tillage [71], but overall energy benefits are less obvious when the embodied energy of herbicides is included [90]. Traffic-induced surface compaction is a challenge for effective seeding in many no-tillage systems, and regular deep tillage is used in some environments to ameliorate the compaction caused by uncontrolled field traffic. Deep tillage is energy-intensive, but most compaction issues can be avoided, and other benefits are achieved using CTF, together with no-tillage. Controlled traffic systems (sometimes referred to as no-traffic farming systems) restrict all field traffic to narrow permanent lanes (sometimes termed 'tramlines'), leaving the rest of the field area unaffected by wheels or tracks [6, 13]. The concept can be traced as far back as the 1850s and was originally associated with gantry or wide-span implement carriers that were designed to reduce the soil problems associated with heavy steam traction engines [19]. Gantry systems allowed a single vehicle to cover a larger area in a single pass. Most of the detailed research occurred in the USA and the UK in the 1960s and 1970s with one company, Dowler, commercializing a 12 m-wide unit. In practice, these early units were sold largely to research organizations, facilitating the accumulation of a significant body of literature on zero-traffic agriculture.

A range of gantry units have subsequently been developed, and some have been used for specialized commercial applications such as vegetable harvesting. Chamen et al. [20] investigated the effects of a partial 12 m-wide gantry system on energy consumption and concluded that it could potentially reduce fuel consumption by up to 44%. However, take-up has been limited, partly because of the difficulty of adapting them for harvesting grain, forage, or root crops. To some extent, this issue has been addressed more recently by the development of the NEXAT^{TM} system in Europe. NEXAT^{TM} is a wide-span interchangeable carrier vehicle that, depending on its configuration, enables the implementation of controlled traffic farming using modules widths of 6 to 24 m. This means that up to 95% of the field cropped area may be kept free from wheeling [65]. Some standard tractors are designed to allow modification of their wheel track 'gauge' width to match that of most grain and other types of harvesters, which are usually 3 m. The concept was originally demonstrated at field-scale in Texas in the USA, in Scotland, and in Queensland in Australia [91]. This system provided a harvester-compatible tractor track gauge by removing the inner pair of the dual tires from 2WD row-crop tractors and extending the nondriven front steering axle width. Other minor modifications such as outrigger support bearings were sometimes used to avoid overloading rear axle bearings. Anecdotal reports of improved soil condition and crop yields came from several Australian farmers, largely on the Darling Downs region of Queensland (Australia), who adopted 3-m controlled traffic systems in the 1980s. Similar systems were adopted in many countries, and on a large-scale in the central highlands of Queensland as a result of an on-farm R&D program in the 1990s [97]. At about the same time, work in the high rainfall zones of Victoria and Western Australia successfully addressed the issue of water logging using a similar approach by forming 1.5–2.0 m 'raised beds' that a tractor and harvester could then straddle. Permanent traffic lanes could be achieved in these systems by using a seeder and harvester of the same width, with a sprayer and fertilizer spreader a multiple of that width. In grain production, this allowed permanent traffic lanes to occupy 10–15% of the field area. This system was adopted by many farmers, but the nontrafficked 'bed' area was easily compromised by poor steering accuracy. In the mid-1990s, the development of RTK (real-time kinematic) positioning auto steer (1 cm positional accuracy) by a small Australian company, Beeline Technologies, completed what is now recognized as a basic controlled traffic farming (CTF) system. The essentials of the CTF system, as defined by the Australian Controlled Traffic Farming Association (ACTFA), include [6]:

- All machinery having the same, or modular, working and track gauge widths, to allow the establishment of permanent traffic lanes;
- All machinery being capable of precise guidance along these permanent traffic lanes; and
- Farm, paddock, and permanent traffic lane layouts arranged to optimize surface drainage and logistics.

In isolation, CTF provides significant advantages and is regarded as the basis for integrating several other practices and technology, such as:

- Minimal soil disturbance, preferably no-tillage or, at most, strip-tillage;
- More intensive cropping frequency and cover crops to maximize biomass production and provide a greater return of crop residues to the system;
- Precise management such as interrow seeding and accurate application of chemicals and fertilizer;
- Spatial monitoring, mapping, and management (e.g., yield mapping and subsequent zonal management, if required) at a progressively finer scale within a defined spatial framework, resulting in permanent traffic and crop zones; and
- Accurate and repeatable on-farm research trials based on a defined spatial framework and spatial technologies.

Several major farm machinery manufacturing companies now provide equipment that is more readily compatible with CTF. Smaller companies have made a valuable contribution by providing properly engineered extensions for tractors with steerable, front-driven wheels. The scale of CTF operations has increased so that the largest commercial systems are now based on an 18-m module (that is, 18 m seeder and combine harvester, 54 m sprayer, and an extendable 'catcher' on the grain chaser bin allowing it to stay on the neighboring set of traffic lanes when the harvester is unloading into the bin).

The broad productive and environmental benefits of CTF have been set out in earlier work [91] and placed within a broader environmental and sustainability context [6, 29, 93]. Surveys indicated that CTF adoption levels in Australia are $> 50\%$ of the total grain crop area for the northern region (which comprises of the growing regions of Queensland and New South Wales), and about 30% of the total grain area (which also includes Tasmania, and South and Western Australia) [92]. CTF adoption in the grain industry has increased considerably since then. There has also been substantial adoption of CTF in cotton production, but effectiveness has been limited by the dual tire requirement of modern cotton-picking machines [18, 46]. Sugarcane cropping has also seen an increase in CTF adoption, albeit at slower rate than that observed in grain systems because of the inherent complexity of sugarcane mechanization. The preponderance of different, contractor-operated equipment has restricted CTF adoption in horticulture [59], except where growers accept that their crop options are limited to those where a modular equipment track gauge and operating width is possible. CTF systems are now also in use in areas of grain production in Alberta (Canada) and Iowa (USA). CTF is also used in several countries in Europe, for example, in Slovakia [28] and the UK [32].

Energy Savings with Controlled Traffic Farming Systems

Controlled traffic farming (CTF) was originally looked at as a method of overcoming the problems of soil compaction, but both research and farmer experience have demonstrated several other substantial advantages some of which are a direct consequence of reduced compaction. These include [13]:

- Reduced energy requirements for field traffic;
- Improved soil structure and rainfall infiltration;
- Reduced runoff and erosion, and therefore nutrients and sediment transport to water courses;
- Enhanced soil macro-biota, particularly earthworms;
- Reduced N_2O emissions and improved crop N uptake and therefore use efficiency; and
- Improved field access that extends the possible operating period for an operation such as spraying.

Tractive power, and its loss in travel reduction 'wheel slip' and motion 'rolling' resistance, is central to fuel efficiency and overall tractor performance. The magnitude of the energy lost in rolling resistance can be approximated, knowing that the best tractive efficiency of four-wheel drive (4WD) tractors on firm soil surfaces rarely exceeds 80% [98]. If 80% of axle power is converted to tractive power, and only 5–7% can normally be attributed to travel loss due to wheel slip, the balance of 13–15% power loss can be attributed to rolling resistance. Tire flexure is largely elastic so less than 1.5% of rolling resistance power loss is usually attributed to the tires. The balance of between 10 and 14% of power output can be accounted for by soil deformation (that is, soil compaction). This is largely plastic deformation of field-moist soil [48]. Detailed consideration of compaction mechanics is beyond the scope of this review. Suffice to say that, as a general rule, compaction damage increases with heavier axle loads, greater soil-tire contact pressures, and for most practical purposes, greater soil water content. The first pass of any given traffic event produces the greatest damage, with repeated passes resulting in much smaller effects, if other factors remain unchanged.

Tractive power, and its efficient transmission, was an important concern when tillage was the major task but, even then, surveys indicated that most tractor tillage operations were carried out at wheel slip levels substantially less than the optimum. This implies that tractive efficiency was less than optimal. However, the economic value of a small degree of tractive 'inefficiency' was seen as less significant than the inefficiency and inconvenience resulting from difficulties working through soft or heavy soil areas of a field. Tractive efficiency loss from wheel slip is only relevant to draught field operations like tillage, where the tractor's main function is the provision of tractive power via the drawbar or hydraulic linkage. Rolling resistance, on the other hand, is relevant to all field operations, where machines traverse the soil. This resistance to forward motion is related to machine weight, soil conditions, and machinery running gear (tires, tracks, or belts), and it is the largest single power requirement for most spraying and logistics operations, and a significant aspect in harvesting. Optimizing wheel slip and reducing rolling resistance result in lower soil damage and reduced fuel consumption. CTF might be expected to provide a significant reduction in rolling resistance if all field traffic is confined to hard permanent lanes, but data is relatively scarce. It has been observed, for instance, that when one wheel follows another, the motion resistance of the second, similar wheel can be halved [9]. Under practical farm conditions, however, there will be substantial differences between wheel parameters of the various wheel sets of the various machines used (e.g., seeding tractor/air cart, sprayer, and harvester/chaser bin). There will also be a substantial time lapse between the passages of various machines, during which wetting and/or drying will change surface soil conditions. Tests performed in the low rainfall zone of the state of Victoria (Australia) demonstrated that the motion resistance of equipment operating on permanent traffic lanes of these relatively rigid soils was approximately 25% less than that of wheels on nontrafficked soil [56, 57]. This result also corresponded with the mean of the grower's assessments of the fuel impact of CTF [45]. Rather greater CTF effects have been measured on the more plastic soils of Southern Queensland (Australia). CTF was also shown to provide yield benefits and substantial fuel savings on the North China Plains [21]. These observations suggest that CTF has the potential to significantly reduce the energy requirements of all soil-engaging operations, and specifically for tillage operations, it was shown that CTF could reduce energy requirements by up to 50% [89].

Modeling work [30] further showed that the absence of soil compaction in the crop zones in CTF systems led to a significant reduction of draft force required in tillage operations consequently reducing fuel consumption by 23% compared with random traffic operations. When comparing conventional traffic management and no-tillage with CTF management and no-tillage operations, fuel consumption was reduced by of over 20%, representing a diesel saving of about 19 L ha^{-1} [21]. The use of CTF in Victoria and Queensland (Australia) was reported [56, 57] to reduce tillage draft on permanent crop beds while improving traction and reducing rolling resistance on compacted permanent traffic lanes, resulting in 40% energy savings compared with the energy required for random traffic operations. A broader assessment of overall CTF effects on the energy requirements of crop production can be found in Tullberg [90]. Farmers often note the timing benefits provided by improved trafficability of permanent traffic lanes and more rapid field access after rain. This is particularly important in herbicide weed control but can apply to most farming operations. In one of the few studies on this topic [60] it was observed that CTF allowed seeding an average of eight days earlier than non-CTF cropping in the Burdekin area of Queensland, and its major impact on the reliability of double cropping in that area.

Other Benefits of Controlled Traffic Farming Systems

Soil compaction is defined as an increase in soil bulk density, which in mechanized agriculture is commonly caused by traffic of farm machinery [82]. This implies a loss of voids between and within soil particles and structural units of the soil profile. The larger voids are generally the first to be lost, with the constriction of progressively smaller voids with increased degree of compaction. Loss of voids might be expected to influence parameters such as infiltration rate as confirmed in earlier work on a Vertisol in Southeast Queensland (Australia) [55]. The four-year study by Li et al. [55] assessed the impact of tillage and traffic on runoff from replicated, annually cropped plots, and its results demonstrated that controlled traffic reduced mean annual runoff by 31% compared with annually wheeled treatments, and that no-tillage reduced runoff by 19%. Controlled traffic with no-tillage reduced annual runoff by 46% and increased grain yield by 16% compared with wheeled, tilled treatments. Results by Li et al. [55] agreed with those reported by Ngo-Cong et al. [66] who showed that a 10–20% increase in soil bulk density, due to compaction, reduced cumulative (steady-state) infiltration by 55–82%, and the available water storage capacity by 3–49%, depending upon the soil type. Wheel impact from heavy vehicles on infiltration was further investigated by Fullen [27]. Rainfall simulator tests were used on a range of wheeling treatments and residue cover levels on previously non-tilled, nonwheeled soil. An inverse relationship between steady-state infiltration and the energy dissipated in the soil by wheeling treatments was demonstrated, providing the soil surface was adequately protected by crop residues. Surface degradation was shown to be related to rainfall energy, but subsoil degradation was related to imposing heavy wheel energy. Radford et al. [73], observed the impact of field traffic on a neighboring degraded Vertisol using soil parameters that related to soil porosity and soil structure. Their assessments considered soil structure in 100 mm increments to depth (subsoil). This cropping soil had been ameliorated through multiple natural wetting and drying events over the course of two crop cycles. Wheel damage to soil structure remained unchanged through this process, while amelioration moved down through the profile of nonwheeled soils beyond 300 mm, but compaction lasted about five years. Available water for growing plants in the top 300 mm of nonwheeled soil was 50% greater than that of wheel compacted soil. These research plots were untouched for two years after completion of this study, during which time they grew a sequence of weed populations. This provided the opportunity for a new set of soil structural assessments which showed little change in the ameliorated condition of nonwheeled soil. The wheel compacted soil treatment had been ameliorated to some extent. However, a single pass by a tractor wheel returned the structural condition and plant available water capacity of the nonwheeled treatment to its original, degraded state. These same replicated runoff plots were also used to investigate tillage and traffic effect on soil biota. Pangnakorn et al. [70] sampled them at approximately six-week intervals over a two-year period that included three cropping cycles; times when the soil profile was close to the wilting point; and times when it was near field capacity. Soil samples were taken to a depth of 150 mm, then earthworms and other macrofauna were assessed by manual sieving, with mesofauna and microfauna extracted by standard funnel methodology. Their study [70] confirmed anecdotal reports of greater earthworm numbers in CTF. Compared with tilled and wheel compacted soil, earthworm numbers were roughly doubled in wheeled no-tillage treatments. They have doubled again in nonwheeled, no-tillage treatments that replicated CTF. Soil arthropods (such as springtails, mites) were slightly more common under controlled traffic conditions [70], an effect consistent with results from Tasmania [76]. Burrows formed by earthworms and arthropods are likely to have contributed to the improved infiltration capacity of no-tillage and nonwheeled treatments.

Wheeling and tillage effects on soil microbiota (nematodes, bacteria, and fungi) appeared to be relatively small, and there were no significant treatment effects on total nematode numbers. Interestingly these results demonstrated that no-tillage CTF soils hosted a much greater percentage of free-living (non-parasitic) nematodes and a much smaller percentage of parasitic nematodes. Independent studies of permanent bed vegetable production [84] have noted similar effects and beneficial outcomes. Given the well-known association between water logging and loss of soil N [54], CTF might be expected to reduce the loss of soil N, and the accompanying emissions of N_2O, a GHG with approximately 300 times the global warming potential of CO_2.These effects were demonstrated through work undertaken to assess soil emissions from CTF beds, freshly wheeled CTF beds and CTF permanent traffic lanes between seeding and harvesting, taking an average of 14 sets of replicated chamber measurements per crop from 15 different grain crops across Queensland, Victoria and Western Australia over four years [88]. Results from that work [88] showed that N_2O emissions from wheeled soils were normally at least twice those of nonwheeled CTF beds. Nonwheeled soil also absorbed methane, which was emitted in small quantities by wheeled areas. In terms of CO_2 equivalent per winter cereal crop, average emissions from wheeled and nonwheeled CTF beds in temperate southern regions were 562 kg ha^{-1} and 265 kg ha^{-1}, respectively, indicating that CTF should reduce emissions by between 150 and 200 kg ha^{-1} and suggesting a reduction in denitrification losses of 10 kg ha^{-1} of N or greater. Equivalent data for sub-tropical northern region crops (4 winter cereals, 2 summer sorghum) indicated that reductions in both emissions and N loss were, approximately, 50% of southern region values. Nitrogen saved in N_2O emissions translates into improved fertilizer N use efficiency, albeit the effect is small [72].

Controlled Traffic Farming Operations in Complex Topography

On undulating terrain, contour operations by farm machinery, usually between contour banks, has long been a recommended practice, such as in the northern cropping regions of Australia. The objective of contour operations is to reduce the risk of water erosion following rainfall. Runoff water will initially run close to the contour, between the ridges formed by the tillage or planting equipment until it reaches a low point, or the flow increases enough to break out from the ridges and to then flow directly downslope to the contour bank. This process will often lead to the formation of rills, but the soil will settle in the contour channel, and so it is not lost. In severe rainfall events, these rills can be substantial and soil movement to the contour bank can block the channel or reduce its water-carrying capacity so that the water then overflows and breaks out of the contour bank. This concentrated runoff can cascade from one contour bank to the next progressively down a hillside paddock, producing significant gullies and making it unfarmable. Yule [97], aware that contour banks were usually designed for the '10-year recurrence interval' storm, appreciated that major erosion events were unavoidable under such a system. It was also observed that severe damage occurred only when the runoff was concentrated and proposed a solution described as 'downslope' CTF operation with widely spaced broad-based drive-over contour banks [97]. Orienting field operations at 90° to the contour will keep most runoff moving within the crop row, or at least within a CTF machine width. With residues anchored to protect the soil surface from droplet impact and better soil structure, infiltration is optimized, and runoff minimized. While controversial when first proposed, downslope CTF is now common in some regions, where occasional high intensity rainfall events occur. It is generally regarded as effective in avoiding major water erosion, but at the cost of limited traffic lane erosion, particularly at the slope change that occurs immediately above the contour channel. The limited data on soil and nutrient loss from these CTF systems suggested that, compared with conventional operations on the contour, downslope systems are effective in limiting damage from major rainfall events, but results have been inconclusive with respect to soil and nutrient loss in minor events [67]. Downslope operations also ensure that traffic lanes drain and largely overcome the problems posed by wet spots delaying field operations. Growers frequently comment on the value of firm permanent tracks in extending the 'operating window', allowing CTF operations to proceed when non-CTF operations cannot. This can produce substantial economic benefits, such as those found by a Queensland CTF farmer who harvested one crop and planted the next crop just a few days after a minor rainfall event. Delay in the field access to a neighboring non-CTF operation resulted in substantial losses when harvesting the crop, and a lost planting opportunity. These aspects can be remarkably important when farm operations must be completed in periods of relatively frequent rainfall. Undisturbed and unseeded traffic lanes are common in Australia's northern region, where water is the major erosion hazard, but in many southern areas wind erosion is the major threat. In this situation, the dry surface soil of bare traffic lanes can be the initiation point of 'blowouts' (these are strips of significant soil loss sometimes found near the crest of ridges after severe winds blowing parallel to strips of bare soil). Such points of blowout typically occur on traffic lanes used repeatedly by sprayers and spreaders, so the problem can usually be dealt with by 'rotating' between different sets of traffic lanes available because the working width of these units is typically a factor of 2 or 3 greater than the seeder and harvester.

Traffic lanes are normally seeded when soil is prone to erosion, but orientation parallel to the prevailing wind is avoided where possible to reduce this possibility. Downslope seeded permanent traffic lanes are common elsewhere, but the topography is obviously a major consideration. Field layout for CTF can be quite straightforward on broad, uniform, shallow slopes, but much more challenging in complex topography. Regardless of traffic lane orientation, efficient logistics must always be a consideration when planning a CTF system. As such, changes to paddock boundaries may be required along with careful sitting of access pathways across long runs in large paddocks. Controlled traffic systems are currently being adapted to different environments with the aim to minimize the area of permanent traffic lanes, minimize soil disturbance, and manage runoff or wind erosion effects.

Embodied Energy

Embodied energy has been defined as the sum of the energy requirements associated directly or indirectly with the delivery of a good or service, that is the energy incorporated or 'embodied' in a product from raw material production through to manufacture, distribution, use and potentially disposal.

Table 3 Components of embodied energy from a machinery operations perspective

Embodied energy	Description	Values or range	References
Machinery	Energy embodied in machinery can be determined from the mass of the different materials of construction and the energy requirements for their fabrication and transport to the user. Method (1): Energy intensity (i.e., embodied energy/mass ratios) across equipment categories. Method (2): Energy intensity can also be expressed per unit purchase price (MJ $\$^{-1}$), or as a percentage of operating energy when depreciated over the expected life of the machine	50–80 MJ kg^{-1}	[90]
Fertilizer	Fertilizer manufacture, particularly N fertilizers, is often identified as a major energy cost of modern agriculture. Fertilizer manufacture has been estimated to consume > 1% of total global energy production, which is largely a consequence of the energy intensity of ammonia production. Poor use efficiency of N and phosphate fertilizer following soil application is also of concern, and global estimates suggested that 50% (or less) of applied N fertilizer is recovered in harvested crops. The balance may be lost through the processes of volatilization, denitrification, leaching and runoff, or immobilized in soil/microbial biomass	Embodied energy in select fertilizers include: N (75.63 MJ kg^{-1}), P (P_2O_5: 9.53 MJ kg^{-1}), K (K_2O: 9.85 MJ kg^{-1}), and S (SO_3: 1.12 MJ kg^{-1})	[8, 12, 58, 71]
Pesticides	Reduced on-farm fuel use in no-tillage systems is offset to some extent by the energy embodied in additional herbicide inputs. Values for common herbicides are quoted in the adjacent column based on a 1999 Canadian publication Recent data on this topic is rare, perhaps because manufacturing technology is proprietary. Values quoted by Helsel [38] were similar, but slightly lower overall, perhaps reflecting improvements in herbicide manufacturing technology	Embodied energy in selected herbicides include (as energy per unit of active ingredient): Glyphosate (511 MJ kg^{-1}), Paraquat (538 MJ kg^{-1}), Diquat (75 MJ kg^{-1}), 2,4 D (336 MJ kg^{-1}), Trifluralin (167 MJ kg^{-1}), and Metolachlor + atrazine (313 MJ kg^{-1}) Or as at the recommended application rates: Glyphosate (225 MJ ha^{-1}), Paraquat (292 MJ ha^{-1}), Diquat (141 MJ ha^{-1}), 2,4 D (37 MJ ha^{-1}), Trifluralin (233 MJ ha^{-1}), and Metolachlor + atrazine (1045 MJ ha^{-1})	[38]
Soil emissions of GHG	Denitrification is an environmental concern because N_2O is produced under near-waterlogged soil conditions when nitrate and carbon are present in the soil (usually from organic matter, crop residue, and applied organic amendments). Methane (CH_4) is also a significant GHG that may be absorbed in small quantities by aerated soils, but produced in rather larger quantities when soil is waterlogged or flooded. Warmer environments and impaired infiltration or drainage may exacerbate this problem	Highly variable, cropping system and environment × management dependent. However, adoption of controlled traffic farming (CTF) coupled with appropriate management of nitrogen (N) fertilizer (that is, ensuring that N application rates match the most economic rate of N) can reduce soil emissions of N_2O by 30% to 50% compared with mechanization systems that do not operate in CTF and where N application rates are above the optimum	[4, 8, 78, 88]

Machinery

Embodied energy has been defined as the sum of the energy requirements associated directly or indirectly with the delivery of a good or service, that is the energy incorporated or 'embodied' in a product from raw material production through to manufacture, distribution, use and potentially disposal [22]. Table 3 details the components of embodied energy from a machinery operations perspective. For machinery, large economic and embodied energy investment is a direct consequence of the low levels of equipment utilization. Equipment contract and sharing arrangements are often suggested to improve utilization, but local arrangements are problematic when most farmers within a district all need to harvest (or seed or spray) at the same time. Substantial improvements can only be achieved by extending equipment operating windows by working across a range of seasons or climate zones. Pollution by nitrogen (N) and other nutrients in fertilizer materials (e.g., phosphorus) represent serious threats to the environment, particularly surface and underground waters [61]. Fertilizer N and phosphorus (P) have both been identified as the major cause of algal blooms and eutrophication of waterways and coastal waters [62, 95]. The embodied energy of herbicides (expressed as MJ ha^{-1}) is large [38] and of similar magnitude to the direct energy requirements of light tillage operations. No account is taken of the scope to reduce active application rates by improved technology (e.g., variable rate technology, precision 'spot' spraying) or the opportunities to avoid herbicide use by improved crop system management or organic farming methods [26]. The issue of herbicide resistance and the need for physical control systems such as targeted tillage, flame, steam, microwave energy or high-pressure water jets are being proposed that might become economic for highly resistant weed control. However, these systems or methods appear to be even more energy-intensive if used to replace overall herbicide spraying.

Sensor-actuated spray systems such as 'WEED-IT' [94] for instance, can ensure herbicide is applied only where green vegetation is detected, reducing the quantity of active ingredients required for effective weed control. When combined with robotic field vehicles (e.g., Swarm farm units) they allow weed control operations, particularly in fallow or terminated cover crops, at frequencies that would otherwise be totally uneconomic. This ensures all weeds are killed while very small, facilitating more profitable use of cover crops and improving cropping systems' sustainability. Such robotic-based system is already being practiced on several Australian farms, but similar innovations are occurring overseas, and so further development of enabling technologies and alternative cropping systems should be expected. One example is the sensors and relay-controlled spray jet units. Individual units are still relatively expensive, so each unit must currently detect and treat swaths of significant width. As these become more affordable over time, narrower swath widths and greater reductions in herbicide requirements will be possible; and while current units can detect only color change, development continues sensors able to distinguish between (e.g., broadleaves and grasses). Lower unit costs and narrower swaths will also allow alternative methods of weed control, potentially including mechanical, steam or microwave treatments, each providing different advantages and limitations compared with herbicide control or overall tillage. A current example is the 'Weed Chipper' developed at the University of Western Australia [36]. The mechanical weed destroyer uses a sweep-equipped chisel plow tine, so its initial application would be in dealing with large, hard-to-kill weeds, but there is clear potential for this technology to operate on a finer scale.

Future Directions

Alternative Energy Sources

A potential solution to more sustainable energy use by farm machinery is to shift toward biofuels or alternative energy sources from renewable resources. The reduction of GHG emissions through the substitution of diesel with biodiesel depends on the feedstock used to provide the triglycerides in the biodiesel, the inter-esterification process utilized in its production, the storage period, and ambient conditions. However, a full life-cycle analysis is needed for any useful comparison to be meaningful. As countries mandate minimum renewable content in diesel fuel, issues around fuel consumption are likely to increase. Reduction of both pollutant emissions and fossil fuel dependency is an objective of energy policies worldwide, and the use of energy efficient vehicles and cleaner energy sources should be encouraged.

Hybrid Electric Vehicles

A hybrid electric vehicle incorporating electric drives in a tractor presents advantages in terms of increased energy use efficiency and expanded functionalities. This higher efficiency leads to a reduction in diesel fuel consumption and hence, a comparable decrease in CO_2 emission. Tractor electrification takes advantage of decoupling loads and drives from the engine which allows operating the latter at its highest efficiency point. Major advantages of machinery electrification are torque and speed control, noise reduction, and a more flexible design. Electric-powered tractors are near to commercialization or are already commercially available. Where the local electricity supply has a low-carbon emission factor, this can also result in a significant reduction in emissions.

Use of Biogas

Biogas powered tractors, where methane (CH_4) can be produced via anaerobic digestion, is also a promising option. Methane has the lowest carbon content of any fuel, the exhaust emissions are odor-free, and the particulate level is up to 98% lower than other tractor fuels. Compared with diesel fuel, CH_4 combustion produces $\sim$ 95% less N_2O and $\sim$ 25% less CO_2. However, a key limitation at present is the ability to accommodate sufficient storage capacity to carry the biogas required for the working hours to make its use efficient.

Lightweight Robotic Equipment and Controlled Traffic

The development of small lightweight robotic equipment has shown potential to undertake functions currently performed by tractor-drawn and other heavy equipment with inherently high fuel consumption. The size and weight limitations ingrained in harvesting and transport technology imply that soil compaction will still be a problem with robotic units. The robotic operation of medium-scale equipment within a precision-controlled traffic farming (CTF) environment should offer technically feasible and energy-efficient alternatives. The integration of weed sensing sprayers with robotic field equipment, CTF and innovative agronomy provide good prospects for sustainable low-energy cropping systems. Sensor-actuated spray systems can ensure herbicide is applied only where green vegetation is detected, reducing the quantity of active ingredients required for effective weed control. When combined with robotic field vehicles they allow weed control operations, particularly in fallow or terminated cover crops, at frequencies that would otherwise be uneconomic. Controlled traffic farming can provide more reliable field access for improved timeliness of operations and better uniformity of soil and crop conditions (as a result of traffic compaction-induced field variability being avoided). Adoption of CTF is known to reduce energy requirements and facilitate more precise relationships between crop rows and machine components or sensors. At the most basic level, better tractor and implement guidance allows interrow 'shield' spraying, on-row crop chemical application or interrow seeding. Increasing precision with RTK tractor and vision-based implement guidance allows precise seed placement in relation to crop residue or growing crops to improve the microenvironment for companion or succession crops.

Conclusions

The review reported in this article highlighted the need for a shift toward increased use of biofuels from renewable sources. This is an important consideration from the sustainability and farm economics perspectives as emissions from energy consumed in agriculture increased by c.a. 25% between 2000 and 2018 to reach $\sim$ 1 Gt CO_2eq, and approximately 15% of agricultural production costs on-farm are energy-related. Gas and diesel oil represent about one-third of the total on-farm energy emissions. The reduction of greenhouse gas (GHG) emissions through the substitution of diesel oil with biodiesel depends on the feedstock, the inter-esterification process, the storage period, and ambient conditions. Increased fuel use efficiency in recent editions of tractors has been achieved by power/load matching and the use of variable transmission. The development of 'intelligent' engine management systems has enabled quick and precise responses to be made to changing conditions and improve overall machine efficiency.

The future for autonomous tractors is promising, however this is not a new concept. Electric-powered tractors are near to commercialization or are already commercially available. Hybrid electric driven tractors present some advantages in terms of increased energy use efficiency and functionalities with potential to decrease CO_2 emissions. Further reductions can be achieved if the local electricity supply transitions toward low-carbon emission technology. Small light-weight robotic equipment can potentially perform functions currently undertaken by tractor-drawn and other farm equipment with high-fuel consumption, provided field operating capacity was not compromised. This is particularly important for key operations such as harvesting. The size/weight limitations in current harvesting equipment mean that soil compaction will still be a problem with robotic units. The robotic operation of medium-scale equipment within a precision-controlled traffic farming environment offers technically feasible and energy-efficient alternatives, and it should be considered in future mechanization developments.

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Declarations

Conflicts of Interest None known.

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