

EVOLUTION OF POWER AND MASS IN SPECIALISED AGRICULTURAL TRACTORS: TREND ANALYSIS

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Abstract. Specialised narrow-profile tractors for vineyards and orchards constitute a critical and technically distinct segment of the agricultural machinery market, operating under strict dimensional constraints that fundamentally differentiate their design logic from that of conventional field tractors. Despite their agronomic importance, the long-term quantitative evolution of their key technical parameters has remained insufficiently characterised. This study investigates the temporal evolution of engine power, machine mass, and derived tyre-to-soil contact pressure across the European and Italian markets over a twenty-three-year period (2001-2023), using a comprehensive database of more than 5,800 commercial models from 22 producers, regularly updated with the support of Edizioni Informatore Agrario srl (Verona, Italy). Temporal trends and inter-variable dependencies were examined through linear regression and descriptive statistics. Results demonstrate that average engine power increased systematically by approximately 31%, from slightly above 50 kW to 65.5 kW, following a strong linear trend ($y = 0.849x$, $R^2 = 0.911$) at a mean rate of approximately 0.67 kW per year, while market diversity progressively narrowed toward higher-power configurations. Average machine mass increased concurrently by 36%, driven by the combined effect of powertrain growth, four-wheel drive adoption, mandatory safety structure integration, emission aftertreatment hardware requirements, and expanding hydraulic and electronic system complexity. As tyre dimensions cannot increase proportionally within the inter-row constraints of orchard and vineyard environments, the growth in machine mass translated directly into a consistent rise in average tyre-to-soil contact pressure, which increased from approximately 0.72 bar in 2001 to approximately 0.86 bar in 2023, a cumulative increase of nearly 20%, characterised by a strong linear trend ($R^2 = 0.919$). This value is now closely approaching the experimentally identified critical threshold of approximately 0.90 bar, beyond which macroporosity undergoes severe and functionally significant degradation. The findings reveal a structurally driven and market-wide trajectory toward heavier machines with higher ground contact pressures, representing a growing and quantifiable risk of soil compaction in specialised perennial cropping systems. These results highlight the need to formally integrate ground pressure as a primary criterion in the design, selection, and regulation of specialised tractors, and to develop high-power, low-mass machine architectures capable of reconciling operational performance with the imperative of long-term soil health preservation.

Keywords: power and mass evolution, specialised tractor, trend analysis.

Introduction

Tractors are the core power unit of agricultural mechanisation, enabling farmers to carry out a wide range of essential operations such as ploughing, tilling, sowing, spraying, harvesting, and transport. Their introduction and continuous evolution fundamentally transformed agricultural productivity by increasing operational capacity, reducing labour dependency, and shortening operation time windows [1]. Since their introduction at the beginning of the twentieth century, agricultural tractors have undergone a continuous process of technological evolution, transforming from simple mechanical substitutes for animal traction into highly powerful and complex machines [2]. Over time, this development has been driven primarily by the increasing demand for productivity, operational efficiency, and the ability to manage larger and heavier implements. This evolution has been characterised not only by functional diversification and increasing automation, but also by a continuous and closely coupled growth in both engine power and machine mass [2; 3]. Early tractors were characterised by low-power outputs and relatively high weight due to inefficient engines and heavy structures. As internal combustion engines became standardised and diesel technology was adopted, tractors progressively achieved higher power levels, while their mass increased to ensure adequate traction and stability [4]. A determined acceleration in both power and mass occurred during the so-called “Golden Age” of tractor development in the 1950s and 1960s. Hydraulic systems became standard, enabling the widespread use of mounted implements and four-wheel drive was introduced. From the late 1960s through the 1980s, the demand for productivity and operational comfort reshaped tractor design. Cabins with safety and noise protection, high-horsepower engines, articulated frames, and specialised large-wheel. Power levels climbed to 80-200 hp, while machine mass reached 6-

12 tonnes. The final decades of the twentieth century introduced electronic control systems, power-shift and continuously variable transmissions, and early digital engine management. Tractors' power reached 120-300 hp range, with masses between 8 and 16 tonnes. The long-term growth has gradually increased the load carried by each wheel by roughly 1 tonne every 17 years (1960-2000), reflecting the ongoing trend toward heavier and more powerful machinery [5]. As a consequence, in parallel to the productivity increase, the relevant concerns regarding the environmental emissions, sustainability and soil compaction intensified.

Table 1

Summary of the historical evolution that provides a concise overview of the main phases of tractor development, highlighting the corresponding ranges of engine power and machine mass across different periods [1; 3; 6; 7]

Period	Years	Average Power Range, hp	Average Mass Range, t
Early development (Agriculture 1.0)	Late 1800s-1910	5-20	1.5-5
Coming of age (Agriculture 2.0)	1910-1938	15-40	2-4
War & post-war expansion (Agriculture 2.0)	1939-1951	30-60	3-6
Golden age (Agriculture 3.0)	1952-1964	40-100	4-7
New generation (Agriculture 3.0)	1965-1980	80-200	6-12
Electronics era (Agriculture 4.0)	1981-2000	120-300	8-16
21st century (Agriculture 5.0)	After 2000	150-600	10-25 +

Modern characteristics of tractors, their efficiency, versatility, and integrated smart technologies (GNSS guidance, automation, precision farming tools, and optimised engines) add additional complications to the selection process. Tractor is an expensive item of farm equipment, and farmers have little control over the price of the tractors and implements. However, the selection logic tools and fleet management solutions [6] can be applied to ease the process. Effective machinery selection is about tailoring the needs of the user to the market offer and making a data-driven decision, a careful match of the technical specifications and market common trends. However, brand loyalty significantly influences purchasing behavior, strong loyalty patterns, especially toward large manufacturers [8; 9]. As a consequence, in large majority cases the tractor choice falls on larger models with higher power. However, oversizing machinery can lead to elevated ownership costs and environmental drawbacks (emissions, soil compaction) [5].

Alongside the general increase in power and size of agricultural tractors, a parallel and equally important trend was the progressive specialisation of tractor designs. As agriculture became diversified and intensified, the traditional concept of a single, general-purpose tractor became insufficient to address the wide variety of crops, terrains, and operational constraints encountered in modern farming. Unlike high-horsepower field tractors, specialised tractors are typically designed around dimensional constraints, such as reduced width, limited height, or specific weight distribution requirements. As a result, their development has focused less on maximising power and more on optimising the relationship between power, mass, stability, and maneuverability.

Over recent decades, increasing planting densities in tree crops have led to progressively narrower inter-row spacing ranging from 0.5 m to 2.4 m and a higher number of plants per hectare [10; 11]. This evolution has been made possible by continuous technological and mechanical advancements in specialised tractors, which have progressively reduced machine size while improving performance and efficiency. As a result, these tractors have not only adapted to modern cultivation systems but have also actively enabled changes in agricultural practices, allowing better exploitation of cultivable areas.

In the Italian context, specialised tractors play a particularly strategic role. With approximately 42% of the territory being hilly and 35% mountainous, a significant share of agricultural activity, especially vineyards and orchards, takes place in areas that are challenging for conventional machinery. In such environments, compact size and high manoeuvrability are essential, making specialised tractors a key component of Italian agriculture and a crucial enabler of its high-value crop production.

The objective of this study was to analyse an extensive database of specialised tractors from the European and Italian markets, covering twenty-three years of data, in order to investigate the evolution of key technical and economic parameters; power and mass.

Materials and methods

The study is dedicated to the comprehensive analysis of the narrow-profile category of tractors used in vineyards and orchards. The reference database includes technical and functional data of more than 5800 commercial models of specialised tractors from leading producers in the European market. The majority of the data consisted of 14 producers, distributed in roughly equal numbers of models, to ensure equal representation of the market. In total database covered data from 22 producers.

The database was created based on the market state of twenty-three years from 2001 to 2023, supplemented with machinery specifications provided by constructors, and regularly updated with the assistance of Edizioni Informatore Agrario srl (Verona, Italy). It should be noted that the timespan of the collected data and the number of analysed models allowed for a well-structured representation of trends.

The raw data collected for the study were sorted by year, edited, and compiled into a single database. Design and performance parameters were classified and homogenised for better understanding of the tractors' data and simplified analysis (Table 2). Analyses were performed for all corresponding variables for each year, as well as a complete analysis and dependencies of the twenty-three years.

Table 2

Description of the considered data according to the information provided by the constructors

Characteristic	Description/Type
Model	Constructing company, series, name
Engine	Power, injection, capacity
Propulsion system	2WD, 4WD
Tractor dimensions	Total length/width/mass
Protective structure	Roll-over protective structures (ROPS)/cabs
List price	Basic machine configuration
Other parameters	Pneumatics, lifting capacity, max and min speed, turning radius

Analyses were carried out using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). Dependencies between the considered variables were studied with the application of linear regression analyses. The relevance of the models was quantified by means of correlation studies and dependence models were defined according to a linear characteristic equation defined by the slope (or linear coefficient) m_i related to the i -th independent variable and by the intercept q between y and x variables.

Results and discussion

One of the most important parameters observed during the analysis is the average power (expressed in kW), which over time has shown a clear and progressive increase, rising from a value slightly above 50 kW to 65.5 kW, corresponding to an average increase of 31%. This increase trend was well-described by a linear regression model ($y = 0.849x$), indicating that average power increased at a mean rate of approximately 0.63 kW per year (Fig. 1).

Nevertheless, there has been a trend toward a slightly less diversified availability of machines, with models becoming more standardised and converging toward increasingly higher power levels. The systematic nature of this trend was demonstrated by a high coefficient of determination ($R^2 > 0.9$).

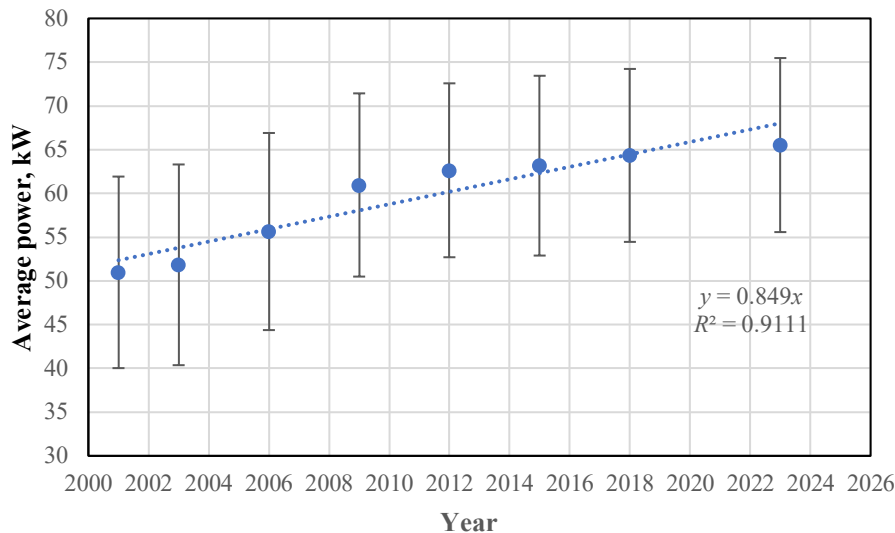


Fig. 1. Trend of average power of specialised tractors over 2001-2023

Alongside the increase in average power, tractors have also experienced an increase in average mass, rising from around 2.2 t to approximately 2.99 t, corresponding to an average increase of approximately 36%. (Fig. 2). This increase trend was well-described by a linear regression model ($y = 31.983x$), indicating that average mass increased at a mean rate of approximately $0.36 \text{ t} \cdot \text{year}^{-1}$.

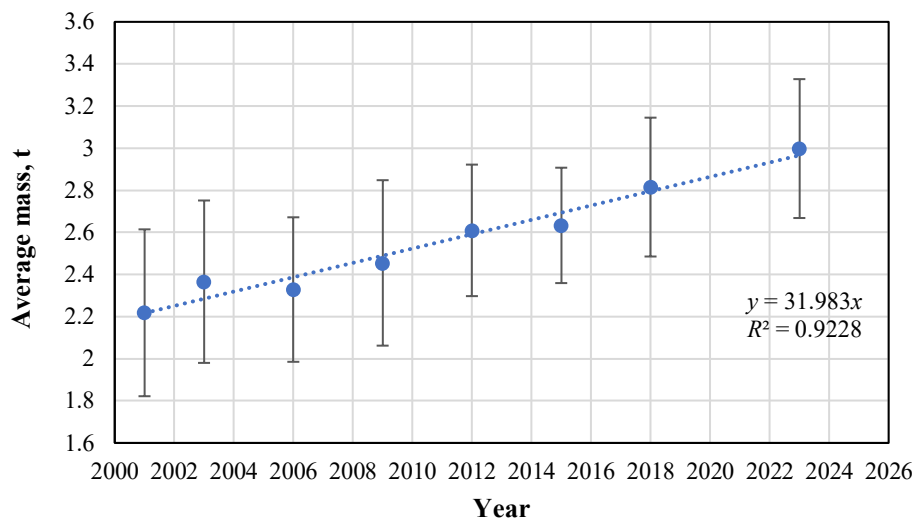


Fig. 2. Trend of average mass of specialised tractors over 2001-2023

The observed increase in average mass of specialised tractors over the study period was the result of several converging technical and regulatory drivers, each contributing additional structural weight to the machine. The most fundamental cause was the growth in engine power itself (Fig. 1). Another significant contributor to the increasing mass was the widespread adoption of four-wheel drive (4WD) systems. The progressive shift from two-wheel drive configurations to mechanical front-wheel drive (MFWD) and full 4WD added substantial structural weight through front axle assemblies, drive shafts, and differentials, while simultaneously increasing traction capability on the slopes and uneven terrain typical of specialised crop environments [1; 6].

With the increase in the tractor mass, an adjustment in tyre dimensions has become necessary in order to address the issue of excessive ground pressure. Tyre sizing, however, must also comply with constraints related to accessibility in orchards and vineyards; for this reason, it cannot increase substantially, leading to a progressive rise in ground pressure. A consistent upward trend in ground pressure over the years was evident, with a coefficient of determination $R^2 > 0.9$.

Under these assumptions, the calculation of ground pressure showed that in the early 2000s an average value of approximately 0.72 bar was observed, whereas for tractors in 2023 the average ground pressure reached about 0.86 bar, corresponding to an increase of roughly 20% over a 23-year period (Fig. 3).

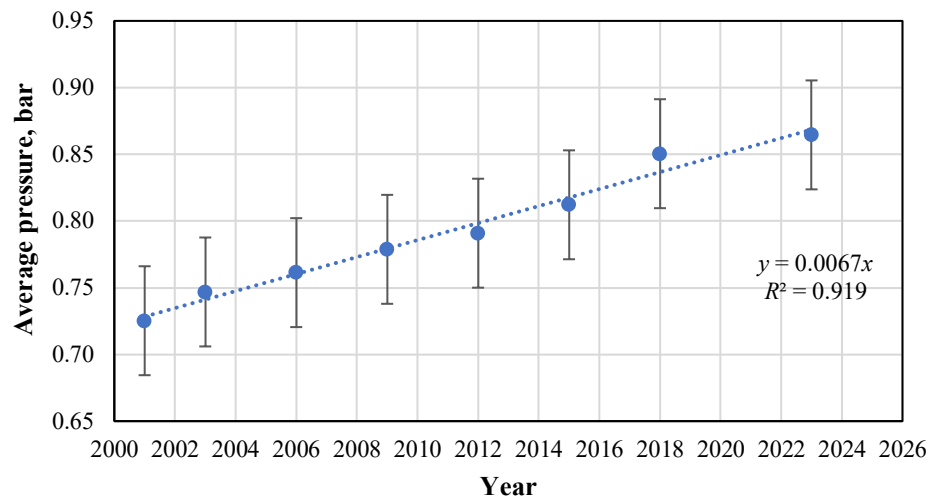


Fig. 3. Trend of average pressure of specialised tractors over 2001-2023

This trend carries significant agronomic and environmental implications: ground contact pressure is recognised as the primary determinant of topsoil compaction, governing pore structure degradation in the tilled layer and reducing the macroporosity critical for root development and water infiltration [12], [13; 14], and recent experimental evidence has identified approximately 0.90 bar as a critical threshold beyond which macroporosity undergoes its most severe reduction, a value that the average specialised tractor fleet is now closely approaching [15].

Conclusions

This study provides the first systematic, medium-term quantitative characterisation of the technical evolution of specialised narrow-profile tractors in the European and Italian markets over a twenty-three-year period, based on a comprehensive dataset of more than 5,800 commercial models. Three principal conclusions emerge from the analysis. First, for the study period, the average engine power of specialised tractors increased significantly and steadily from approximately 50 kW in 2001 to 65.5 kW in 2023 with a cumulative increase of about 31% following a strong linear trend ($R^2 > 0.9$) with a mean rate of about 0.67 kW annually. This progression reflects a structural and market-wide shift toward higher-power platforms, driven by growing operational demands, implement complexity, and the progressive displacement of lower-power models from the active commercial offer. Second, the increase in engine power was accompanied by a consistent and closely coupled growth in average machine mass, arising from multiple converging technical and regulatory drivers: the enlargement of powertrains, and the widespread adoption of four-wheel drive systems. Crucially, in the specialised tractor segment, these mass increments cannot be compensated by proportional increases in tyre contact area due to the strict inter-row dimensional constraints of vineyard and orchard environments. Third, and most critically, the constrained tyre dimensions have caused the growing machine mass to translate directly into a consistent rise in average tyre-to-soil contact pressure, which increased from approximately 0.72 bar in the early 2000s to approximately 0.86 bar by 2023 with a 20% increase characterised by a strong linear trend ($R^2 > 0.9$). This trajectory is now placing the average specialised tractor fleet in close proximity to the experimentally identified critical pressure threshold of approximately 0.90 bar, beyond which macroporosity undergoes severe structural degradation. Collectively, these results demonstrate that the pursuit of higher power and operational capability in specialised tractors has generated a measurable and growing mechanical pressure on the soil resource, and that ground contact pressure should be formally integrated as a primary design and procurement criterion in the specialised tractor segment alongside conventional performance indicators. Future research should focus on the development of low-mass, high-power tractor architectures and on the validation of pressure-based selection

frameworks that reconcile operational performance with soil health preservation over the multi-decade productive lifespan of perennial cropping systems.

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Conceptualization, T.Y. and F.M.; methodology, T.Y. and F.M.; software, T.Y. and D.K.Y.; validation, A.C.; formal analysis, T.Y. and D.K.; investigation, T.Y. and D.K.; data curation, T.Y. and D.K.; writing – original draft preparation, T.Y. and D.K.; writing – review and editing, A.C. and M.S.; visualization, A.C.; project administration, F.M. All authors have read and agreed to the published version of the manuscript.

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