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Comparing vegetative growth patterns of cultivated (*Daucus carota* L. subsp. *sativus*) and wild carrots (*Daucus carota* L. subsp. *carota*) to eliminate genetic contamination from weed to crop

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ABSTRACT

Wild carrot is a problematic weed that can threaten the genetic purity of cultivated carrots by hybridization. Wild carrots must be controlled before flowering to avoid the undesirable crossing with cultivated carrots. Understanding wild carrot's vegetative growth pattern helps formulate sustainable weed management practices. However, little is known about the vegetative growth patterns of wild and cultivated carrots. A pot experiment was carried out to compare and model the vegetative growth pattern of different morphological traits in both wild and cultivated carrots. This study was executed in a glasshouse located in Palmerston North, New Zealand. A factorial randomized complete block design (RCBD) with two factors and four replications was used. The first factor was assigned to the carrot genotype (cultivated and wild) and the second factor to length of juvenile stages (12-weeks, 8-weeks, and 4-weeks). Plant height, leaf number, shoot fresh and dry weight, root fresh and dry weight, root diameter and root length were measured. Data were analyzed using analysis of variance (ANOVA), principal component analysis (PCA), correlation, and regression analysis. At the 8-week juvenile stage (9–11 leaves stage), wild carrot's shoot and root characteristics exhibited rapid growth. Correlation analysis indicated positive and significant ($p < 0.05$) correlations between above and below-ground morphological traits. PCA showed that morphological characteristics, except plant height, can be used to distinguish wild and cultivated carrots. To predict the vegetative growth pattern of most of the morphological traits of wild and cultivated carrots, power regression models were selected based on higher R^2 and *adj-*R^2 values and lower values of *RMSE*, *AIC* and *BIC*. The study showed wild carrots grew more quickly than cultivated carrots during the vegetative phase. It is recommended that appropriate weed management practices, such as hoeing, tilling, hand pulling, or herbicide spraying, be implemented before wild carrot leaf stages 9–11.

1. Introduction

Weed infestation is one of the key factors restricting crop production globally [1]. Approximately, 31.5 % of the yield loss is caused by about 1800 weed species resulting in annual economic losses of USD 32 billion [2]. Numerous region-specific and local abiotic, biotic, and anthropogenic factors have an impact on weed infestations [3,4]. On a global scale, weeds and invasive alien plants have generated issues in agro-ecosystems as a result of changes in their geographical distribution and population densities [5]. Due to the significant spatiotemporal variability and genetic diversity of the weed population, identifying the specific variables linked to effective weed management is important [6].

Carrot (*Daucus carota* L. subsp. *sativus*) is a member of the family Apiaceae. It is a widely consumed vegetable due to its high nutritional characteristics, especially vitamin A [7,8]. As a result, the consumption of carrots and related products has expanded gradually [9]. In the United States, per capita consumption of carrots has increased over the last century, rising from 2.2 pounds (~1 kg) in 1919 to an estimated 8.8 pounds (~4 kg) in 2022 [10]. Hence, global demand for carrots is climbing, generating an increased market for carrot producers and a

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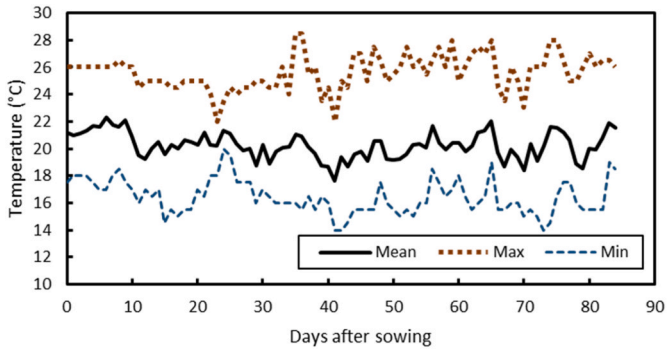

Fig. 1. Temperature in the glasshouse during the study period.

consequent requirement for carrot seeds [11]. Although farm inputs such as fertilizers, pesticides, and herbicides are important to enhance carrot productivity, genetically superior seeds are unavoidable inputs for the establishment of plants and transfer of desirable traits to subsequent offspring [12]. Therefore, the production of genetically pure carrot seeds needs to be guaranteed to meet the quality requirements of carrot root producers, where the seed is the only planting material used to propagate and establish carrot seedlings [13].

The production of high-quality carrot seeds is influenced by the temperate climate, where long days are necessary for seed formation during all growth phases, with the exception of vernalization [14]. Vernalization, which happens throughout the winter months (low temperature under short-day conditions), induces the transition from the vegetative phase to the reproductive phase of carrot seed crops [15]. The growth phase of carrots prior to the low-temperature vernalization is known as juvenility. This phase generally ends after reaching the 8–12 leaves stage, which can be reached by 12 weeks from seed sowing. Due to this, the present study consists of different lengths of juvenile phases with a maximum of 12 weeks [16]. Carrot seeds are mainly produced from open-pollinated and hybrid seed crops worldwide [17], even though the hybrid carrot seed crop sector is expanding in New Zealand for the production of genetically pure carrot seeds [18]. In hybrid carrot seed production, male fertile lines and male sterile lines, generally known as cytoplasmic male sterile lines (CMS), serve as pollen donors (paternal parent) and pollen receptors (maternal parent), respectively [16]. Insect pollinators, such as honeybees (*Apis mellifera* L.), Calliphorid flies (*Calliphora vicina*), nectar scarabs, and hoverflies (*Eristalis tenax*) facilitate the transfer of pollen to the receptive stigmas [19,20]. Such a pollen distribution mechanism makes it possible for unwanted pollen to flow from carrot cultivars with undesirable features as well as wild carrots [21].

Wild carrot (*Daucus carota* L. subsp. *carota*) also belongs to the Apiaceae family. Wild carrot is often referred to as Queen Anne's lace and is considered a serious weed in several parts of the world [22]. Studies have indicated that European colonization was one of the reasons for the dispersal of wild carrots across the globe [23]. Depending on the geographical location and climatic conditions, wild carrots can exhibit annual, biennial or perennial growth habits [21]. Moreover, previous literature indicated that the wild carrot can be grown in open habitats, especially in wastelands and roadsides [24]. Furthermore, wild carrots appear to be adaptable to a wide range of soil conditions [25] and can sustain themselves in challenging soil conditions [26]. Since the cultivated carrot and wild carrot are sexually compatible relatives, hybridization is possible between wild and cultivated carrots. Furthermore, a broad variety of insect species from 15 different families are attracted to the wild carrot flowers. The same pollinators may also forage flowers of cultivated carrots. During the pollination process, wild and cultivated carrots can compete with one another to attract pollinators. As a result, pollen transmission from wild-type to cultivated carrot is feasible and reciprocal [21]. However, gene flow from wild to cultivated carrots can negatively impact commercial carrot seed production, where the possibility of a loss of genetic purity can be expected in carrot seeds. A commercial carrot seed line may be unsaleable in the target market if it contains characteristics of wild type [27,28]. Genetically impure seed lots are often identified by the presence of early bolters in cultivated fields when hybrids between crop and wild plants flower early, yielding less edible, white-rooted carrots [29,30]. To avoid undesirable hybridization, a 1 to 2 mile (1.6 km–3.2 km) isolation distance from wild carrots should be maintained during commercial carrot seed production [31]. However, crop-weed hybridization continues to be a significant issue thus deteriorating the genetic purity of cultivated carrot seeds [30]. Furthermore, the local commercial carrot seed industries are under constraint, particularly for expansion, due to the dramatic increase in the spread of wild carrots in carrot seed producing regions, including New Zealand and the United States, over the past few years [18,32]. To minimize outcrossing and seed rain, wild carrots need to be controlled before flowering. It is therefore important to understand the vegetative growth pattern of wild carrots to enable the implementation of weed management strategies. From a breeding point of view, the introgression is advantageous, where the beneficial characteristics of wild carrots, such as environmental adaptability, disease resistance, and abiotic stress tolerance, can be introduced into cultivated carrots via breeding programmes [28,33].

Table 1
Factors and treatment combinations used in the experiment.

Carrot Genotype	Juvenile stage (Date of sowing)	Combination of treatments
Cultivated (T_1)	12-week (26th July)- J_1	T_1J_1
	8-week (23rd August)- J_2	T_1J_2
	4-week (20th September)- J_3	T_1J_3
Wild (T_2)	12-week (26th July)- J_1	T_2J_1
	8-week (23rd August)- J_2	T_2J_2
	4-week (20th September)- J_3	T_2J_3

Understanding the morphological characteristics of weed species by evaluating their growth patterns assists in developing weed management strategies prior to the critical period of weed control [34,35]. In agriculture, growth curves are widely utilized as a tool to analyze and simulate how plants grow over time and in response to certain climatic circumstances [36,37]. Generally, growth models are developed based on mathematical functions through various regression analyses, such as linear, non-linear and probit analysis [38]. Consequently, several statistical criteria, including the coefficient of determination (R^2), adjusted coefficient of determination (*adj* R^2), root mean square error (*RMSE*), Akaike Information Criteria (*AIC*), and Bayesian information criterion (*BIC*), can be used to find satisfactory growth curve fitting [39,40].

Although many studies have examined the growth pattern of cultivated carrots, there are no studies that compared and modelled the growth pattern of wild and cultivated carrots together in the context of controlling wild carrots, particularly in New Zealand. This is a significant research gap in the existing scientific literature relevant to the management of wild carrots for the production of quality commercial carrot seeds. Integrating data on wild carrot phenology and weed biology can significantly enhance wild carrot control strategies. In this study, we aimed to compare the various morphological traits of wild and cultivated carrots at different vegetative stages (4 weeks, 8 weeks, and 12 weeks), as well as predict the optimal wild carrot growth stage at which to implement the essential weed management practices to control the wild carrots near the carrot seed-growing sites. Furthermore, determining the relationship between the above and below-ground morphological traits of wild and cultivated carrots makes it easier to understand how both plants' root systems grow without having to uproot them. To make inferences, various statistical methods were used including ANOVA (analysis of variance), PCA (principal component analysis), regression analysis, and correlation. The findings from this study facilitate the timely management of wild carrots, especially before

Table 2
Effect (mean analysis) of different juvenile stages on morphological parameters of two different genotypes of carrots.

Genotype	Juvenile period	Plant height (cm)	Number of leaves	Shoot fresh weight (g)	Shoot dry weight (g)	Root length (cm)	Root diameter (mm)	Root fresh weight (g)	Root dry weight (g)
Cultivated	12 weeks	38.05 ± 0.88	8.23^{bc}±0.17	17.16^{b} ± 1.01	2.98^{b} ± 0.24	10.39^{b} ± 0.65	23.78^{a}±0.85	18.88^{a}±1.51	2.88^{a}±0.33
	8 weeks	25.52 ± 1.02	5.73^{cd} ± 0.18	3.69^{cd} ± 0.37	0.59^{cd} ± 0.06	8.14^{b} ± 0.57	7.68^{c}±0.59	1.40^{c}±0.25	0.16^{c}±0.03
	4 weeks	8.92 ± 0.37	1.94^{e}±0.08	0.09^{d} ± 0.01	0.02^{d} ± 0.003	2.65^{c}±0.13	0.78^{e}±0.06	0.01^{c}±0.003	0.001^{c}±1.69 × 10^{-4}
Wild	12 weeks	35.95 ± 1.22	25.00^{a}±1.81	25.75^{a}±2.13	5.22^{a}±0.45	19.79^{a}±1.45	9.81^{b} ± 0.53	6.98^{b} ± 0.68	1.74^{b} ± 0.21
	8 weeks	25.84 ± 0.94	10.34^{b} ± 0.80	4.93^{c}±0.79	0.91^{c}±0.13	9.89^{b} ± 0.84	4.91^{d} ± 0.30	0.75^{c}±0.13	0.17^{c}±0.02
	4 weeks	8.35 ± 0.35	2.50^{de} ± 0.10	0.08^{d} ± 0.01	0.02^{d} ± 0.003	2.80^{c}±0.24	0.75^{e}±0.04	0.01^{c}±0.003	0.002^{c}±2.24 × 10^{-4}

Means followed by the same letter(s) in each column are not significantly different based on Tukey's Test.

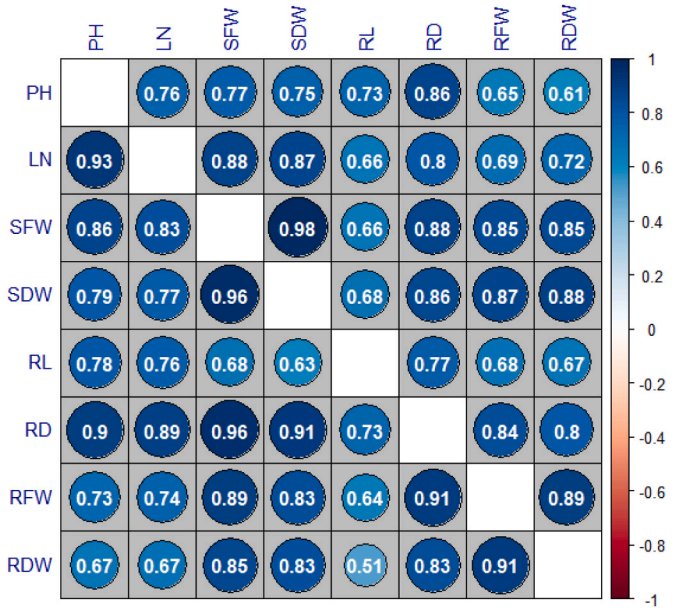

Fig. 2. Correlation matrix between morphological traits of wild and cultivated carrots; Upper diagonal-wild carrots and lower diagonal-cultivated carrots; keys: PH- plant height, LN- Leaves number, SFW- shoot fresh weight, SDW- shoot dry weight, RL-root length, RD-root diameter, RFW- root fresh weight, RDW- root dry weight.

flowering, which helps to produce genetically pure commercial carrot seeds through the prevention of undesirable pollen flow from wild to cultivated carrots. Additionally, the descriptive results on morphological characteristics obtained from this research could be used to formulate crop simulation models (CSM) for both wild and cultivated carrots in future.

2. Material and methods

2.1. Experiment location

The study was conducted in a glasshouse at the Plant Growth Unit, Massey University, Palmerston North, New Zealand (40°22′40.9″S 175°36′49.1″ E), from 26th July to 16th October 2022. The dimensions of the glasshouse were 15 m (length) and 6 m (width), with heights of 3.5 m and 1.7 m at the highest and lowest points. The daily air temperature was recorded with an electronic DS1923 temperature logger (iButton®) throughout the study period (Fig. 1). The average, maximum and minimum temperatures were 20.25 °C, 25.62 °C and 16.44 °C, respectively.

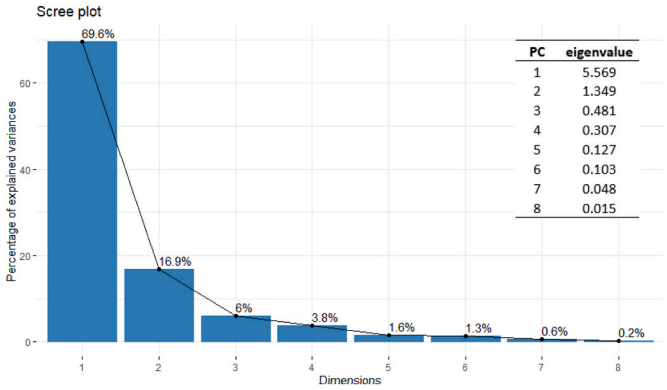

Fig. 3. Scree plot of variability % against the number of PCs for morphological attributes and a table for PCs Vs eigenvalue.

Table 3
Correlation of all morphological traits to PC 1 and PC 2 for wild and cultivated carrots.

Morphological trait	PC 1	PC 2
PH	0.872	−0.002
LN	0.735	0.602
RL	0.742	0.389
RD	0.816	−0.507
SFW	0.938	0.212
RFW	0.789	−0.566
SDW	0.913	0.272
RDW	0.848	−0.372

Keys: PH- plant height, LN- Leaves number, SFW- shoot fresh weight, SDW- shoot dry weight, RL-root length, RD-root diameter, RFW- root fresh weight, RDW- root dry weight.

Depending on the temperature within the glasshouse, the windows automatically opened to allow fresh air to circulate. Day length was extended to provide long day conditions (18 h light and 6 h dark) to the carrot seedlings by using cool daylight fluorescent lights (Philips TLD 58w/865) in the glasshouse. Light metre (LI-COR; Model LI-250) measurements were used to determine the light intensity, which was maintained between 140 and 150 μmol $m^{-2}s^{-1}$ throughout the experiment [14].

2.2. Planting materials, seedling establishment and crop husbandry

Both cultivated and wild carrots were grown in this study. Seeds of wild carrots were collected from Dairy One farm, Massey University in Palmerston North, New Zealand (40°22′31.0″ S 175°36′21.3″ E) in May

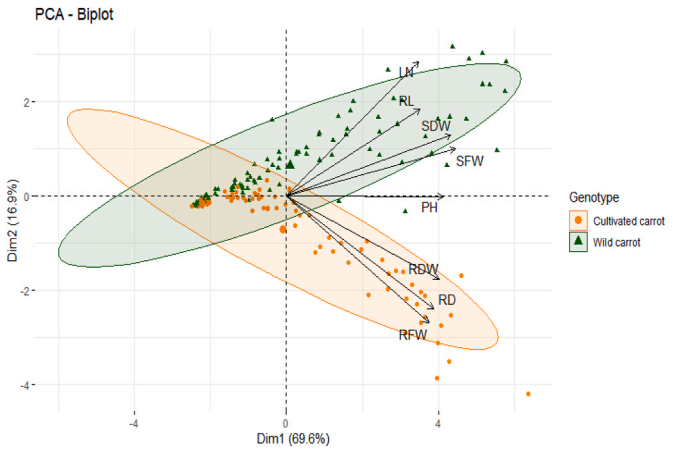

Fig. 4. Principal component analysis of wild and cultivated carrots based on the morphological parameters. These parameters included PH (Plant height), LN (Leaves number), SFW (Shoot fresh weight), SDW (Shoot dry weight), RL (Root length), RD (Root diameter), RFW (Root fresh weight), and RDW (Root dry weight). The scatter plot displays the distribution of sampled plants (either wild or cultivated) according to PC 1 and PC 2.

2022. Cultivated carrot seeds (No 27 Male lines) were sourced from South Pacific Seeds Ltd, New Zealand. PVC pipes (Marley OPTIM® DWV Pipe SN6) with a 10 cm diameter and a 50 cm height were filled with potting mixture and used to grow the plants from seed [14]. To improve the drainage of excess irrigation, garden nets were placed over the bottom of each pot. According to Yadav et al. [41], the potting mixture used was prepared by mixing garden soil and sand in a 3:1 ratio with a concrete mixer. Subsequently, the pots were filled with 4 L of potting mixture and 8–9 months slow-releasing fertilizer (Osmocot Exact Standard, 15N-3.9P-9.1 K + 1.2 Mg + Trace elements) at the rate of 4 g/L. Cultivated and wild carrot seeds were sown on 26 July, 23 August, and 20 September 2022 to provide 12-week, 8-week and 4-week-old plants, respectively. Seeds were sown at a rate of 3 seeds per pot. A spray lance attached to the seedling nozzle was used for irrigation until seedling emergence. Following that, drippers were used to irrigate plants at the rate of 4 ml/day/plant throughout the experiment. Emerged seedlings were thinned to one plant per pot once they had three unfolded true leaves [42]. Over the entire duration of the study, manual weeding was done every week. Moreover, there were no pests and diseases observed during the experiment.

2.3. Treatment combinations and experimental design

The pot experiment was laid out according to a two-factor factorial arrangement in a randomized complete block design (RCBD) with four blocks per treatment. The two factors were carrot genotype (2 levels) and juvenile period of the carrot plant (3 levels), resulting in six treatment combinations (Table 1). Within each sowing date treatment block, plants were completely randomized. Each block comprised 9 pots per

Table 4
Fitted models to estimate predicted values of different morphological traits of cultivated carrots as a function of duration from sowing (time).

	R^2	Adj. R^2	RMSE	AIC	BIC	Derived equation
Plant height (PH)						
Linear	0.868	0.866	4.450	396.197	402.811	$PH_{CL} = 3.492T - 4.464$
Quadratic	0.870	0.866	4.419	397.241	406.059	$PH_{CQ} = -0.071T^2 + 4.615T - 8.173$
Log-linear	0.823	0.821	0.272	21.901	28.515	$PH_{CE} = 4.6715e^{0.1796T}$
Log-log	0.857	0.855	0.245	7.728	14.342	$PH_{CP} = 1.4573T^{1.3121}$
No of leaves (LN)						
Linear	0.884	0.882	0.913	183.968	190.582	$LN_{CL} = 0.771T - 0.923$
Quadratic	0.903	0.900	0.834	173.882	182.700	$LN_{CQ} = -0.049T^2 + 1.557T - 3.521$
Log-linear	0.838	0.835	0.265	18.259	24.873	$LN_{CE} = 1.0045e^{0.1841T}$
Log-log	0.894	0.893	0.214	−10.330	−3.716	$LN_{CP} = 0.2944T^{1.3622}$
Shoot fresh weight (SFW)						
Linear	0.777	0.774	3.417	360.792	367.406	$SFW_{CL} = 1.95T - 9.144$
Quadratic	0.869	0.865	2.616	327.001	335.820	$SFW_{CQ} = 0.293T^2 - 2.709T + 6.246$
Log-linear	0.880	0.878	0.813	168.380	174.994	$SFW_{CE} = 0.0065e^{0.6729T}$
Log-log	0.910	0.908	0.706	149.540	156.154	$SFW_{CP} = 9E\text{-}05T^{4.8981}$
Shoot dry weight (SDW)						
Linear	0.773	0.770	0.575	122.052	128.666	$SDW_{CL} = 0.325T - 1.524$
Quadratic	0.867	0.863	0.441	88.338	97.157	$SDW_{CQ} = 0.049T^2 - 0.459T + 1.065$
Log-linear	0.901	0.900	0.705	149.336	155.950	$SDW_{CE} = 0.0014e^{0.6501T}$
Log-log	0.928	0.927	0.600	127.709	134.323	$SDW_{CP} = 2E\text{-}05T^{4.7252}$
Root length (RL)						
Linear	0.548	0.541	2.989	342.870	349.484	$RL_{CL} = 1.005T - 1.108$
Quadratic	0.558	0.545	2.954	343.288	352.107	$RL_{CQ} = -0.061T^2 + 1.973x - 4.305$
Log-linear	0.551	0.544	0.492	101.174	107.788	$RL_{CE} = 1.4316e^{0.1667T}$
Log-log	0.589	0.583	0.471	95.286	101.900	$RL_{CP} = 0.4705T^{1.234}$
Root diameter (RD)						
Linear	0.856	0.854	3.793	374.766	381.381	$RD_{CL} = 2.825T - 12.099$
Quadratic	0.917	0.914	2.886	340.181	349.000	$RD_{CQ} = 0.328T^2 - 2.389T + 5.124$
Log-linear	0.905	0.904	0.459	91.673	98.287	$RD_{CE} = 0.148e^{0.4329T}$
Log-log	0.920	0.919	0.422	80.386	87.000	$RD_{CP} = 0.0096T^{3.1248}$
Root fresh weight (RFW)						
Linear	0.609	0.603	5.839	432.585	439.199	$RFW_{CL} = 2.228T - 11.348$
Quadratic	0.768	0.761	4.496	399.575	408.394	$RFW_{CQ} = 0.496T^2 - 5.666T + 14.73$
Log-linear	0.902	0.901	1.195	220.057	226.671	$RFW_{CE} = 4E\text{-}05e^{1.1103T}$
Log-log	0.913	0.912	1.128	212.318	218.932	$RFW_{CP} = 3E\text{-}08T^{7.9972}$
Root dry weight (RDW)						
Linear	0.490	0.482	1.032	200.339	206.953	$RDW_{CL} = 0.309T - 1.582$
Quadratic	0.625	0.613	0.885	181.748	190.567	$RDW_{CQ} = 0.071T^2 - 0.816T + 2.134$
Log-linear	0.904	0.902	1.046	196.330	202.853	$RDW_{CE} = 2E\text{-}05e^{0.98662T}$
Log-log	0.906	0.905	1.034	194.842	201.365	$RDW_{CP} = 4E\text{-}08T^{7.0968}$

T, time from sowing (weeks); $_C$; cultivated carrot; $_L$-linear; $_Q$-quadratic; $_E$-exponential; $_P$- power; R^2, coefficient of determinant; *adj.* R^2, adjusted coefficient of determinant, *RMSE*, root mean square error; *AIC*, Akaike Information Criteria; *BIC*, Bayesian information criterion.

Table 5
Fitted models to estimate predicted values of different morphological traits of wild carrots as a function of duration from sowing (time).

	R^2	Adj. R^2	RMSE	AIC	BIC	Derived equation
Plant height (PH)						
Linear	0.761	0.757	6.153	471.969	478.799	$PH_{WL} = 3.417T - 3.857$
Quadratic	0.783	0.776	5.864	467.030	476.137	$PH_{WQ} = -0.246T^2 + 7.402T - 17.454$
Log-linear	0.782	0.779	0.303	38.551	45.381	$PH_{WE} = 4.6202e^{0.1793T}$
Log-log	0.847	0.844	0.255	13.439	20.269	$PH_{WP} = 1.2981T^{1.3604}$
No of leaves (LN)						
Linear	0.582	0.577	7.544	501.306	508.136	$LN_{WL} = 2.777T - 9.795$
Quadratic	0.598	0.586	7.403	500.596	509.703	$LN_{WQ} = 0.191T^2 - 0.320T + 0.774$
Log-linear	0.823	0.821	0.403	79.334	86.164	$LN_{WE} = 0.9282e^{0.2706T}$
Log-log	0.837	0.835	0.387	73.472	80.302	$LN_{WP} = 0.1552T^{1.9906}$
Shoot fresh weight (SFW)						
Linear	0.567	0.561	8.968	526.211	533.041	$SFW_{WL} = 3.2T - 15.602$
Quadratic	0.629	0.618	8.309	517.216	526.322	$SFW_{WQ} = 0.445T^2 - 4.01T + 9.002$
Log-linear	0.852	0.850	0.956	203.786	210.616	$SFW_{WE} = 0.0056e^{0.7155T}$
Log-log	0.892	0.891	0.816	180.992	187.822	$SFW_{WP} = 4E\text{-}05T^{5.3403}$
Shoot dry weight (SDW)						
Linear	0.560	0.553	1.883	301.434	308.264	$SDW_{WL} = 0.661T - 3.274$
Quadratic	0.632	0.621	1.721	290.521	299.628	$SDW_{WQ} = 0.101T^2 - 0.968T + 2.287$
Log-linear	0.864	0.863	0.851	187.082	193.912	$SDW_{WE} = 0.0018e^{0.6698T}$
Log-log	0.896	0.894	0.746	168.156	174.986	$SDW_{WP} = 2E\text{-}05T^{4.973}$
Root length (RL)						
Linear	0.563	0.557	5.706	461.113	467.943	$RL_{WL} = 2.018T - 5.633$
Quadratic	0.567	0.554	5.682	462.495	471.602	$RL_{WQ} = 0.07T^2 + 0.891T - 1.788$
Log-linear	0.683	0.678	0.519	115.922	122.752	$RL_{WE} = 1.0839e^{0.2374T}$
Log-log	0.705	0.701	0.501	110.723	117.553	$RL_{WP} = 0.2197T^{1.7598}$
Root diameter (RD)						
Linear	0.733	0.729	2.179	322.482	329.312	$RD_{WL} = 1.125T - 3.846$
Quadratic	0.734	0.726	2.175	324.220	333.327	$RD_{WQ} = 0.017T^2 + 0.845T - 2.889$
Log-linear	0.808	0.806	0.485	106.210	113.040	$RD_{WE} = 0.2625e^{0.3106T}$
Log-log	0.861	0.859	0.414	83.213	90.043	$RD_{WP} = 0.0302T^{2.3377}$
Root fresh weight (RFW)						
Linear	0.515	0.508	2.789	358.043	364.873	$RFW_{WL} = 0.8958T - 4.6546$
Quadratic	0.614	0.603	2.488	343.605	352.712	$RFW_{WQ} = 0.166T^2 - 1.796T + 4.533$
Log-linear	0.854	0.852	1.209	237.613	244.443	$RFW_{WE} = 0.0001e^{0.9098T}$
Log-log	0.888	0.886	1.059	218.556	225.386	$RFW_{WP} = 3E\text{-}07T^{6.7669}$
Root dry weight (RDW)						
Linear	0.452	0.444	0.800	178.127	184.957	$RDW_{WL} = 0.226T - 1.187$
Quadratic	0.546	0.533	0.727	166.471	175.577	$RDW_{WQ} = 0.044T^2 - 0.484T + 1.237$
Log-linear	0.854	0.852	1.097	220.608	227.396	$RDW_{WE} = 7.5E\text{-}05e^{0.8312T}$
Log-log	0.880	0.878	0.993	206.475	213.263	$RDW_{WP} = 3E\text{-}07T^{6.1706}$

T, time from sowing (weeks); $_W$; wild carrot; $_L$-linear; $_Q$-quadratic; $_E$-exponential; $_P$- power; R^2, coefficient of determinant; *adj.* R^2, adjusted coefficient of determinant, *RMSE*, root mean square error; *AIC*, Akaike Information Criteria; *BIC*, Bayesian information criterion.

treatment combination (n = 9). In total, 216 plants (6 treatment combinations × 4 blocks × 9 plants per block) were accommodated in the glasshouse.

2.4. Sampling and measurements

All the plants were removed from their pots on October 16, 2022, in order to collect data on the quantitative morphological parameters at different growth stages (4, 8 and 12 weeks), such as fresh and dry weight of shoot (g), root length (cm), root diameter (mm) and fresh and dry weight of root (g). Prior to uprooting the samples, plant height (cm) was measured from the ground level to the top of the apex of the longest leaf using a measuring tape. While the number of leaves was determined by counting leaves from each sample [43], root length was measured from the base to the top of the root by using a ruler [44]. Root diameter was measured by using a 150 mm digital vernier caliper (Craftright, China) [45]. Fresh and dry weights of the shoots and roots were estimated using digital balances (Mettler Toledo PM 6100 Balance and Mettler Toledo AE100 Analytical Balance). After measuring the fresh weight, the root and shoot samples were separated and placed in paper bags to dry at 60 °C until reaching constant weight [46].

2.5. Statistical analysis

Evaluation of both main and interaction effects between carrot genotype and juvenile stages of carrot seedlings was evaluated using a two-way analysis of variance (ANOVA) in the general linear model. Subsequently, a mean comparison was undertaken using Tukey's test at a 5 % significance level ($p < 0.05$). A Scree plot and eigenvalues (>1) were used for the selection of appropriate principal components (PCs) as a prerequisite to the PCA [47]. Thereafter, PCA biplot was plotted to distinguish the wild and cultivated carrots via clusters and to find out the importance of morphological traits in distinguishing the wild and cultivated carrots. Pearson correlation analyses were executed to study the relationship between the morphological traits of both wild and cultivated carrots, especially to compare the correlation between above and below-ground traits. To understand the growth pattern over time, four different models (linear, quadratic, log-linear and log-log) were evaluated using linear and nonlinear regression approaches. The exponential and power growth models were derived from log-linear and log-log functions, respectively. The acquired data from different morphological traits was randomly split into a training dataset (70 %) and a test dataset (30 %). The training and test datasets were used to calibrate and validate the selected models, respectively [48]. The following statistical criteria were applied to each mathematical function's adjustment and selection: coefficient of determination (R^2), adjusted coefficient of determination (*adj* R^2), root mean square error (*RMSE*), Akaike Information Criteria (*AIC*), and Bayesian information criterion (*BIC*). R studio (version 2022.07.2 + 576) was used for all statistical analyses.

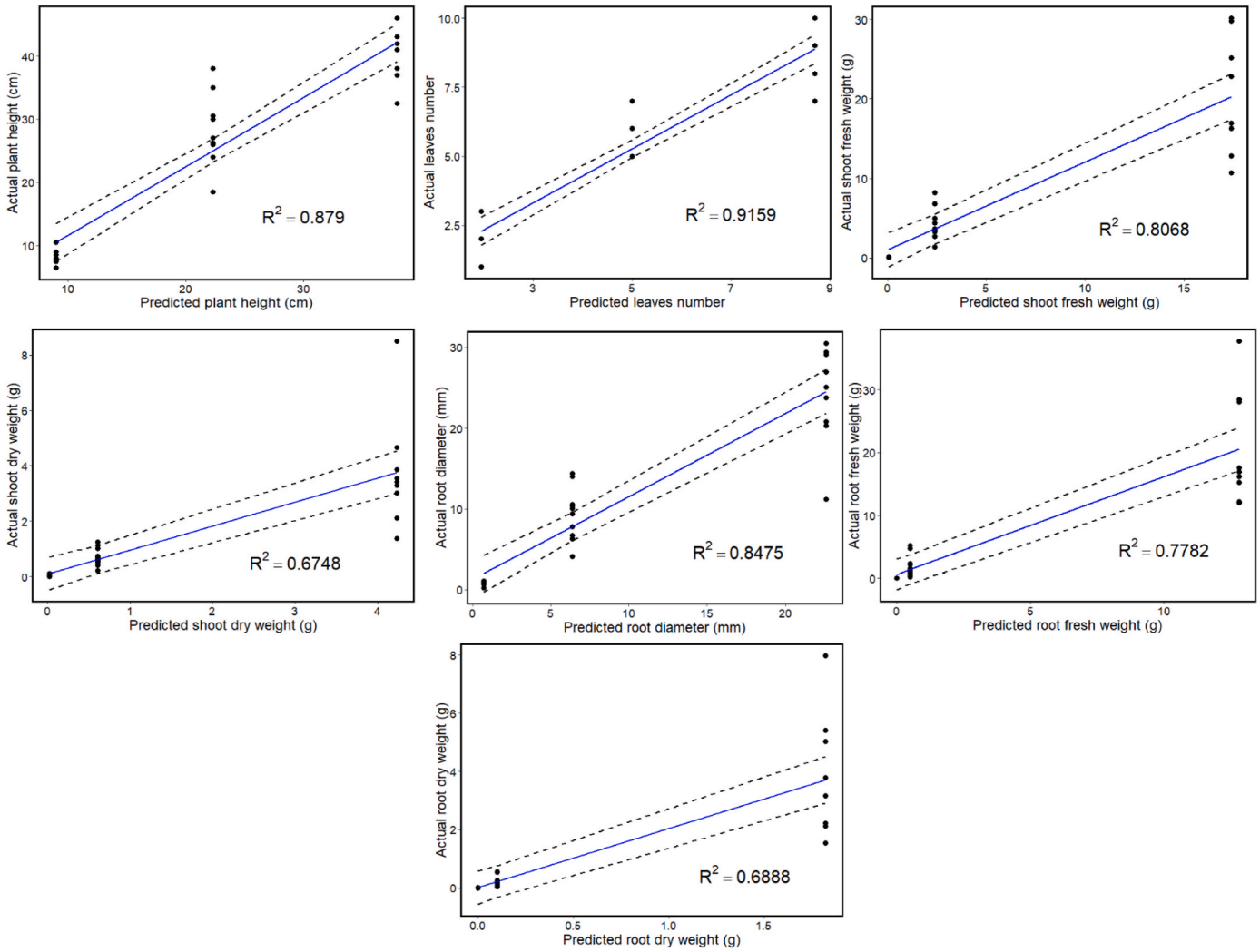

Fig. 5. Predicted values vs actual values for validation data set using selected regression models of the morphological traits of cultivated carrots.

3. Results and discussion

3.1. Effect of genotype and juvenile period on morphological traits

The results of the ANOVA and Tukey's test for the morphological traits of wild and cultivated carrots are shown in Table S1 and Table 2, respectively. The interaction effect between genotype and juvenile period was significant ($p < 0.05$) for all morphological traits except plant height.

3.1.1. Plant height

In developing weed management strategies, weed height is an important deciding factor [49]. There was no significant ($p > 0.05$) difference between the wild and cultivated carrots in terms of plant height if taken at the same juvenile stage, but there was a significant ($p < 0.05$) increase in plant height with increasing length of the juvenile period (Table 2). At the 12-week juvenile stage, the height of the cultivated and wild carrots was reported as (38.05 ± 0.88 cm) and (35.95 ± 1.22 cm), respectively. When comparing plant heights of wild (25.1–33.9 cm) and commercial (31.6 cm) carrot populations from Norway, Sweden, and Denmark, the New Zealand wild and cultivated carrots have exhibited a higher growth rate [50]. This demonstrates how the genotype of carrots, especially wild carrots, is different in terms of morphology all across the world [51]. Furthermore, the plant height of cultivated and wild carrots has increased by 76.56 % and 76.77 %, respectively from 4 weeks to 12 weeks of juvenile stage. Relatively, the highest increment of plant height was reported as 17.49 cm for wild carrots and as 16.60 cm for cultivated carrots between 4 and 8 weeks after sowing. This highlights the significance of managing weeds in the early phases of growth; once they enter the rapid growth stage, wild carrots are extremely challenging to manage. Similar findings were made by [52]; who discovered that wild carrots can be completely controlled by using herbicides such as 2,4,5-T when they are between 15.24 cm and 20.32 cm (6–8 inches) in height. Meanwhile [53], have revealed that several combinations of Picloram + 2,4-D and Triclopyr + clopyralid were effective in controlling the wild carrots at a height of 9–11 cm. Furthermore [54], used wild carrot plants with heights of 11–20 cm and 26–28 cm to compare the effectiveness of pre–emergence and post–emergence herbicides in a non–tillage soybean field in Michigan. Based on these findings, it is clear that the height of the wild carrot needs to be considered when recommending an herbicide. Furthermore, the size of the wild carrots grows along with plant height. Inconsistent weed control is commonly caused by improper herbicidal application due to the huge size of the weed at the time of spraying [55,56]. In order to boost the herbicidal efficacy, the rate of application could be increased to control the weeds. Therefore, it's important to control wild carrots as early as possible to minimize the cost of herbicide application.

3.1.2. Number of leaves

Leaf number is a significant morphological trait used to estimate the

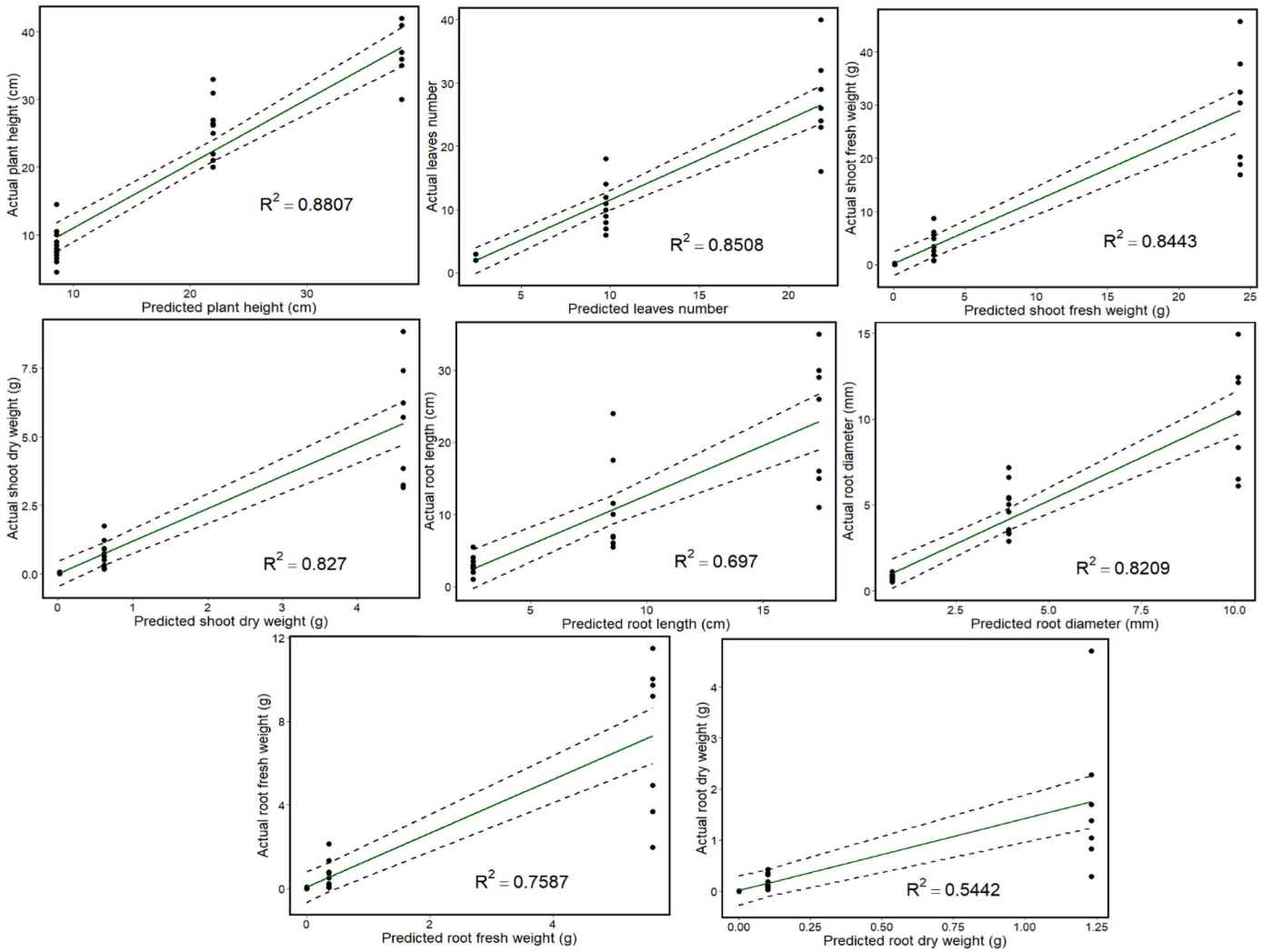

Fig. 6. Predicted values vs actual values for validation data set using selected regression models of the morphological traits of wild carrots.

growth and development of plants [57] and to determine when to spray herbicides more effectively for weed management [58,59]. The leaf number of wild carrots was significantly ($p < 0.05$) higher than the leaf count of cultivated carrots at all the juvenile stages. The highest leaf number was recorded as 25.00 ± 1.81 for wild carrots at 12 weeks after sowing, which was 67.08 % higher than the leaf number produced by cultivated carrots at the same growth stage (Table 2). Similarly, a previous study in the Netherlands showed that the wild carrot has produced approximately 54 % higher number of leaves compared with cultivated carrots at the 15-week juvenile stage [29]. Genetic variation is one of the influencing factors in the difference in leaf count in between wild and cultivated carrots [60]. Furthermore, these findings support the statement made by [61]; who noted that different varieties of the same species could produce varying leaf counts. Moreover, wild and cultivated carrots were shown to have a rapidly increasing trend in leaf counts between the 8 and 12 (by 14.66 leaves) weeks, during the 4 and 8 (by 3.79 leaves) weeks of the juvenile stage, respectively (Table 2). This indicates that the wild carrot needs to be controlled prior to the approximately 9–11 leaves stage (8 weeks of juvenile phase). As a result, the 5–14 leaf stages (average: 9.5 leaves) were chosen for the wild carrot herbicidal efficacy studies [52,62]. This is further supported by [63]; who claimed that the application of an herbicide is successful while the wild carrot is at the seedling stage. Furthermore, determining the weed leaf number at different growth stages is beneficial for formulating weed management strategies, particularly for identifying the rate, time, and type of herbicide application [64].

3.1.3. Shoot fresh and dry weight

Shoot fresh and dry weights are commonly used to study the growth pattern of plants [65]. Larger weeds are extremely more challenging to eradicate than small plants. Therefore, shoot fresh and dry weight should be taken into account when formulating weed management plans and researching their efficacy [66,67]. Shoot fresh and dry weight of wild carrots at the 8 and 12-week juvenile stages were significantly ($p < 0.05$) higher than the cultivated carrots. The highest shoot fresh and dry weight of wild carrots was reported at the 12-week juvenile stage as 25.75 ± 2.13 g and 5.22 ± 0.45 g, respectively. These values were 33 % and 43 % greater than the comparable shoot fresh and dry weights of cultivated carrots. Furthermore, the shoot fresh and dry weights of wild and cultivated carrots were not significantly different ($p > 0.05$) at the 4-week juvenile stage. This illustrates a similar growth pattern of wild and cultivated carrots up to the first 4 weeks. Consequently, the growth trend of wild carrots is quicker than that of cultivated carrots in terms of the fresh and dry weight of the shoots (Table 2). Likewise [29], found that wild carrots had greater shoot dry weights than most carrot cultivars. The shoot features of wild and cultivated carrots differ mostly due to the genetic control of morphological traits. Furthermore, between the 8 and 12 weeks of the juvenile phase, there was a dramatic rise in the shoot's fresh weight (by 80.5 %) and dry weight (by 82.57 %), which emphasizes a focus on managing wild carrots promptly (Table 2). Due to

the variability in biomass at different growth stages [54], have recommended different combinations of herbicides to control wild carrots according to their growth stage (seedling, established and over-wintered wild carrots).

3.1.4. Root length and diameter

Investigating the growth pattern of root length and diameter is essential since the taproot is the economically valuable component of the cultivated carrot [68]. Due to this, root characteristics have been identified and become important criteria in breeding programmes [69]. Furthermore, it is important to understand the wild carrot's growth pattern of below-ground parts from the perspective of weed management [62]. A significant variation ($p < 0.05$) was reported in root length and root diameter among wild and cultivated carrots at all the juvenile phases. The longest root was observed in wild carrots (19.79 ± 1.45 cm) at week 12 of the juvenile stage, which was 47.5 % higher than the root length of cultivated carrots. Whereas, cultivated carrots were shown to have a larger root diameter (23.78 ± 0.85 mm) in the 12 weeks of the juvenile phase, which was 58.8 % wider than wild carrots (Table 2). Genetic mechanisms are the key reasons for variations between wild and cultivated carrots regarding the shape and size of the roots [29]. Particularly, QTLs (quantitative trait locus) on chromosomes 1,2, and 7 were concerned with regulating root length, while a 180 kb region on chromosome 1 was linked to root shoulder diameter [69,70]. Furthermore, a rapid increase in root length was found between the juvenile stages of 4 and 8 weeks, and the 8 and 12 weeks for cultivated and wild carrots, respectively (Table 2). Tilling the surroundings of the carrot seed-producing field can be an effective mechanical weed management method to control wild carrots from a long-term point of view [54]. Furthermore, wild carrot's deep taproot facilitates stock energy for the consequent regrowth and creates difficulties for removal [25]. Although some tillage tools, including rotary hoe, can till up to the depth of 15 cm, wild carrot produces taproots deeper than 19 cm after 12 weeks of the juvenile phase [32]. noted that the partial removal of wild carrots' roots resulted in regeneration and the development of new seedlings in the subsequent seasons. Therefore, it is important to take root length into account and initiate tillage operations or hand-pulling methods to remove the entire plants as early as possible in the wild carrot's life cycle [71].

3.1.5. Root fresh and dry weight

Root biomass is an economically important trait in cultivated carrots. However, this trait can vary between the genotypes of cultivated carrots [72]. There was a significant difference ($p < 0.05$) between wild and cultivated carrots in terms of root fresh and dry weight. Moreover, the highest fresh and dry weight of cultivated carrots was recorded as 18.88 ± 1.51 g and 2.88 ± 0.33 g, respectively at the 12-week juvenile stage. Comparatively, cultivated carrots developed roots that were around three times as large as those of wild carrots (Table 2). A significant signature of cultivated carrots is the development of larger storage roots than wild species [70]. Furthermore, the root fresh and dry weight of both cultivated and wild carrots increased with the increasing juvenile period. This increment was most rapid from 8 to 12 weeks of the juvenile stage for both wild and cultivated carrots compared with the early growth stages (Table 2) [73]. have observed the adaptation of wild carrots to prolonged drought conditions via redistribution of root mass to deeper soil layers. It is very challenging to manage wild carrots after they have increased most root biomass. Therefore, it is important to control wild carrots at the early juvenile stages.

3.2. Correlation analysis

Estimation of the relationship between the morphological traits of wild carrots and commercial carrots via correlation studies can provide details that will help scientists and agronomists in determining the most efficient weed management strategies to control wild carrots in carrot seed-producing regions globally [33,74]. The strength of the correlation coefficients among the examined morphological characteristics also demonstrated how important it is to comprehend how they relate to one another in order to implement sustainable weed management practices [75]. Especially, this evaluation is important to understand the relationship between the above (plant height, leaves number, and shoot fresh and dry weight) and below-ground (root length, root diameter, and root fresh and dry weight) morphological traits of both wild and cultivated carrots, which will help in decision making based on the morphological development of above-ground parts without needing to uproot the plants. The results obtained from the correlation analysis of the morphological traits of wild and cultivated carrots are shown in Fig. 2. Pearson's correlation coefficient (r) revealed a significant ($p < 0.05$) relationship among all the morphological traits of wild and cultivated carrots. The plant height of cultivated carrots was positively and strongly correlated with root length (r = 0.783), root diameter (r = 0.897), and root fresh weight (r = 0.728). It also showed that the leaf number of cultivated carrots positively and strongly correlated with root length (r = 0.764), root diameter (r = 0.887), and root fresh weight (r = 0.740). Furthermore, the root diameter (r = 0.958) and root fresh weight (r = 0.894) of cultivated carrots showed a positive correlation with shoot fresh weight. Moreover, there was a strong and positive correlation (r = 0.908) between the root diameter and root fresh weight of cultivated carrots. Pearson correlation matrix between the morphological traits of wild carrots indicated that root fresh weight was positively correlated with plant height, number of leaves, shoot fresh weight, root length, and root diameter. This positive correlation was strong with shoot fresh weight (r = 0.848) and root diameter (r = 0.839); and moderate with plant height (r = 0.647), number of leaves (r = 0.695), and root length (r = 0.675). Furthermore, root diameter (r = 0.863) and length (r = 0.732) had a positive and strong correlation with plant height in wild carrot plants. Also, both root length and diameter were positively correlated with the number of leaves (r = 0.660 and r = 0.796, respectively) and shoot fresh weight (r = 0.662 and 0.879, respectively). Similar positive correlations have been reported by [76] and [77] in Indian carrot genotypes and hybrid carrot varieties in Ivory Coast, respectively. The positive correlation between the root diameter, root length and root fresh weight with plant height, number of leaves and shoot fresh weight may be accounted for by the higher photosynthetic rates [78]. These findings indicated that the plant height, number of leaves and shoot fresh weight can be used as root trait predictors of both wild and cultivated carrots.

3.3. Principal component analysis

Principal component analysis (PCA) is an analysis method that is frequently used to assist in data exploration and visualization by highlighting variance and revealing significant trends in the dataset [79]. In this study, PCA was done to understand the relative contribution of different morphological traits for evaluating the phenological variability among the wild and cultivated carrots. To facilitate graphical displays of such data matrices, biplot axes were created after estimating eigenvalues, which serve as essential in numerical diagnostics to assess the variation among the 8 morphological variables of both wild and cultivated carrots [80]. Accordingly, the entire variation was split up into 8 principal components (PCs) and a scree plot was generated to display the percentage of variance. The PCA produced two PC groups with an eigenvalue of more than 1, accounting for 86.5 % variability (PC 1, 69.6 % and PC 2, 16.9 %) (Fig. 3). Furthermore, it is evident that all morphological characteristics contribute more to PC 1 than PC 2 based on the correlation between morphological traits and PCs (Table 3). Therefore, cultivated carrots can be distinguished from wild carrots by using morphological traits such as plant height, leaf number, shoot dry and fresh weights, root diameter, root length, and root dry and fresh weight. Consequently, all the morphological traits of wild and cultivated carrots were plotted against PC 1 and PC 2 (Fig. 4).

The findings from PCA indicated that the wild and cultivated carrots could be effectively distinguished and categorized by PC 1 and PC 2 since the PCA biplots clearly clustered the wild and cultivated carrots based on the morphological traits at the vegetative stages (Fig. 4). Furthermore, we found two sets of morphological traits that could differentiate the wild and cultivated carrots from each other in different directions on the PCA biplot (PC 1 vs PC 2). The first group of root-related morphological traits, including RD (root diameter), RFW (root fresh weight), and RDW (root dry weight), showed a positive correlation with one another and the second set of traits included RL (root length), LN (leaves number), SFW (shoot fresh weight), and SDW (shoot dry weight), which efficiently separated among the wild and cultivated carrots in two different quadrants. Moreover, the genotype cluster of cultivated and wild carrots was inclined toward the first and second set of morphological traits, respectively. These findings indicated that wild and cultivated carrots exhibited a significant degree of variability in terms of morphological traits except PH (plant height). The representation from PC 1 and PC 2 illustrates considerable amounts of overlap from left to right (PC 1) and top to bottom (PC2), which is mainly due to the presence of similar morphological characteristics of both wild and cultivated carrots at their early vegetative stage (prior to 4 weeks of age).

3.4. Modeling the growth pattern of wild and cultivated carrots

3.4.1. Model estimation

The summary statistics for the predicted models of cultivated and wild carrots are shown in Table 4 and Table 5, respectively. The growth patterns of both cultivated and wild carrots throughout the juvenile phase were modelled using the linear, quadratic, exponential and power functions [81]. The mathematical functions chosen to simulate and predict the growth of wild and cultivated carrot plants have been selected based on the statistical criteria. Preferred models attain higher R^2 and *adj*-R^2, but lower *RMSE*, *AIC* and *BIC* [37]. The key reason for using four different statistical criteria is to obtain more accurate models by eliminating model overfitting issues [82].

The plant height ($R^2 = 0.857$; $RMSE = 0.245$), leaf number ($R^2 = 0.894$; $RMSE = 0.214$), shoot fresh weight ($R^2 = 0.910$; $RMSE = 0.706$), root diameter ($R^2 = 0.920$; $RMSE = 0.422$), root fresh weight ($R^2 = 0.913$; $RMSE = 1.128$), and root dry weight ($R^2 = 0.906$; $RMSE = 1.034$) of cultivated carrots were fitted to power regression growth pattern, whereas a quadratic function was used to model the shoot dry weight ($R^2 = 0.867$; $RMSE = 0.441$). Instead, for wild carrots, power regression models were used to fit the growth curves resulting from plant height ($R^2 = 0.847$; $RMSE = 0.255$), leaf number ($R^2 = 0.837$; $RMSE = 0.387$), shoot fresh weight ($R^2 = 0.892$; $RMSE = 0.816$), shoot dry weight ($R^2 = 0.896$; $RMSE = 0.746$), root diameter ($R^2 = 0.861$; $RMSE = 0.414$), root fresh weight ($R^2 = 0.888$; $RMSE = 1.059$) and root dry weight ($R^2 = 0.880$; $RMSE = 0.993$). Low R^2 values can signal that a forecast is not precise [83]. Hence, the root length of the cultivated carrot was removed from the model prediction due to the comparatively low regression coefficient ($R^2 < 0.75$). Furthermore [84], showed exponential patterns in the growth of five different hybrid carrot varieties in the Costa Rica region during the early vegetative phase (from 0 to 100 days). This demonstrates the regional variance in the growth pattern of carrot genotypes in their vegetative phase.

3.4.2. Model validation

Model validation is typically used to verify that the chosen models are adequate representations of the real system and to confirm the model's representation of the experimental values is accurate [85]. A validation set of 30 % of the total data, that was not included in the model estimation, was examined in order to validate four different regression models (linear, quadratic, exponential, and power) [86]. The relationship between the predicted and actual values from the validation data set for selected morphological traits of cultivated and wild carrots is illustrated in Figs. 5 and 6, respectively.

Model validation results indicated that the power regression model was the best to predict the growth pattern of plant height ($R^2 = 0.879$), leaf number ($R^2 = 0.9159$), shoot fresh weight ($R^2 = 0.8068$), root diameter ($R^2 = 0.8475$), and root fresh weight ($R^2 = 0.7782$) of cultivated carrots. However, due to the lower R^2 value, models related to the root dry weight ($R^2 = 0.6888$) and shoot dry weight ($R^2 = 0.6748$) of cultivated carrots were excluded from the model prediction. Similarly, the power regression model was shown to be the most accurate in predicting the growth patterns of wild carrots regarding plant height ($R^2 = 0.8807$), leaf number ($R^2 = 0.8508$), shoot fresh weight ($R^2 = 0.8443$), shoot dry weight ($R^2 = 0.827$), root diameter ($R^2 = 0.8209$), and root fresh weight ($R^2 = 0.7587$). On the other hand, root length ($R^2 = 0.697$) and root dry weight ($R^2 = 0.5442$) of wild carrots were not considered for the model prediction due to their inaccuracy.

The findings of the fitted growth curves provided in this study may be utilized to support recommendations for weed control methods during the early growth stage of wild carrots. In particular, the fitted equations can be applied to forecast the wild carrots' growth stage. The wild carrots might then be controlled using the appropriate weed control techniques, such as hand weeding, hoeing, mowing, tilling, and herbicide application according to their growth stages.

4. Conclusion

The primary objective of this study was to assess and model the growth of different morphological traits in both wild and cultivated carrots during their juvenile phase using various statistical approaches. The effect of juvenile period and genotype on the vegetative growth of wild and cultivated carrots was studied using ANOVA statistical methods. Comparatively, wild carrots grew much faster than cultivated carrots in terms of leaf number, shoot fresh weight, shoot dry weight and root length. The growth of these traits was most rapid after 8 weeks of the juvenile stage (9–11 leaves stage). Therefore, it is important to manage the wild carrots before the 9–11 leaves stage. Furthermore, wild carrots can produce taproots of 200 mm in length at the end stage of the juvenile phase. To completely remove the taproot of the wild carrot from the soil profile (thus limiting the possibility of regrowth), the depth of the taproot should be taken into account whilst selecting tillage implements. Likewise, manual weeding should also be done before the stage of 9–11 leaves, at which point the entire wild carrot plant, including the taproot, can be easily pulled out. Meanwhile, when selecting a recommended herbicide to spray, it's crucial to have a better understanding of the wild carrot's growth pattern because the type of herbicide and the rate of application varies according to the stage of growth. Correlation analysis indicated a significant and strong positive correlation between most of the above and below-ground morphological traits of both wild and cultivated carrots. Therefore, decisions impacted by root length, diameter, and weight can be made without uprooting the plants using the above-ground traits, such as plant height and leaf count, because they are easier to measure. PCA results revealed that the wild and cultivated carrots can be distinguished based on morphological traits other than plant height. To model the growth pattern of eight different morphological traits of both wild and cultivated carrots, several regression models were analyzed and discussed in this work. In the field of agriculture, regression models are also frequently used to forecast the complex growth pattern of plant morphological characteristics. Even though four different models were developed from the training data set (70 % of the sample), a power regression model was recommended based on the statistical criteria, such as R^2, *adj*- R^2, *RMSE*, *AIC* and *BIC* to predict all the morphological traits of wild and cultivated carrots except shoot dry weight and root length of cultivated carrots due to the lower accuracy of the model. Instead, a quadratic model was suggested to estimate the growth pattern of the shoot dry weight of cultivated carrots. Validation of the recommended models, especially the quadratic and power model, using the validation data set (30 % of the sample) revealed

a positive relationship ($R^2 > 0.75$) between the predicted and actual data of the selected morphological traits of wild and cultivated carrots from the training data set, except the cultivated carrot's shoot and root dry weights and root length and dry weight of wild carrots. The results of the modeling study indicated that the power regression model can be used to predict the growth pattern of plant height, number of leaves, shoot fresh weight, shoot dry weight (only for wild carrots), root diameter, and root fresh weight of both wild and cultivated carrots. The incorporation of data regarding morphological traits with a growth model offers an efficient tool to improve the management of wild carrots. Moreover, studying the growth pattern of cultivated carrot's morphological traits is beneficial for the farmers, who produce taproots for consumption and steckling production. Furthermore, the findings of this study suggest the significance of incorporating the growth pattern of wild carrots in formulating weed management strategies to prevent their spread. This study also provides information for the decision-making at the farm level and development of regionally specific weed management practices, suppression of wild carrot infestation, and prevention of seed production. In conclusion, these findings considerably advance our current knowledge of managing wild carrots, particularly in the areas around commercial carrot seed production sites. As a last point, we would like to emphasize that this study appears to be the first in the literature to compare and model the vegetative growth pattern of wild and cultivated carrot genotypes in New Zealand.

CRediT authorship contribution statement

Asharp Godwin: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Simone Pieralli:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Svetla Sofkova-Bobcheva:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Andrew Ward:** Supervision, Conceptualization. **Craig McGill:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2024.101213.

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